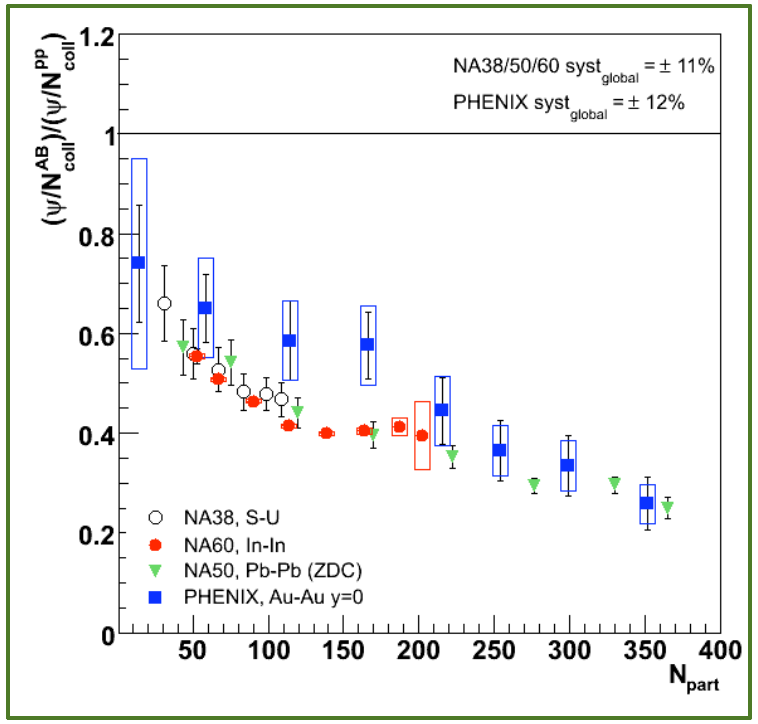
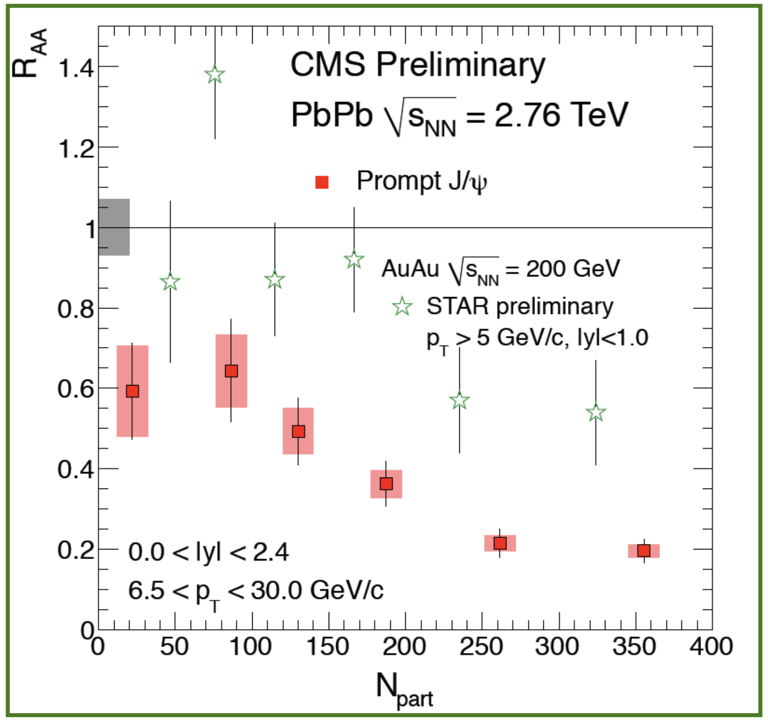
Quarkonium Production in Hot Medium

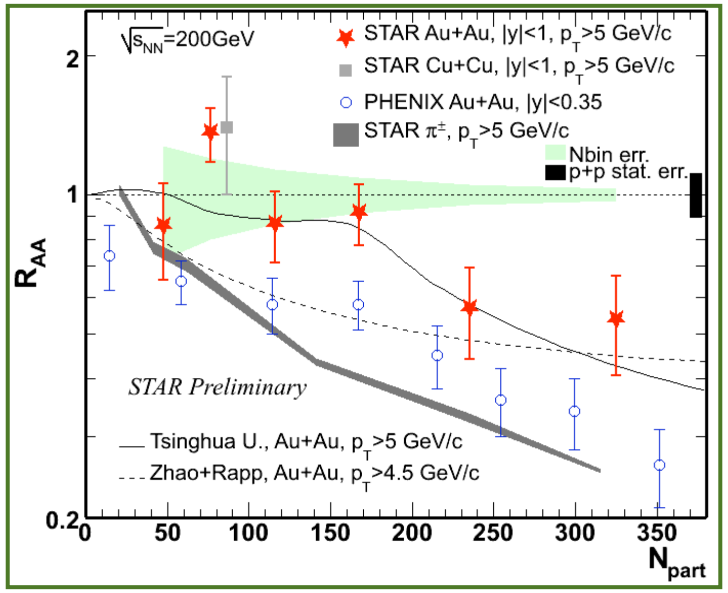
Ágnes Mócsy
Pratt Institute, Brooklyn, New York
Pratt

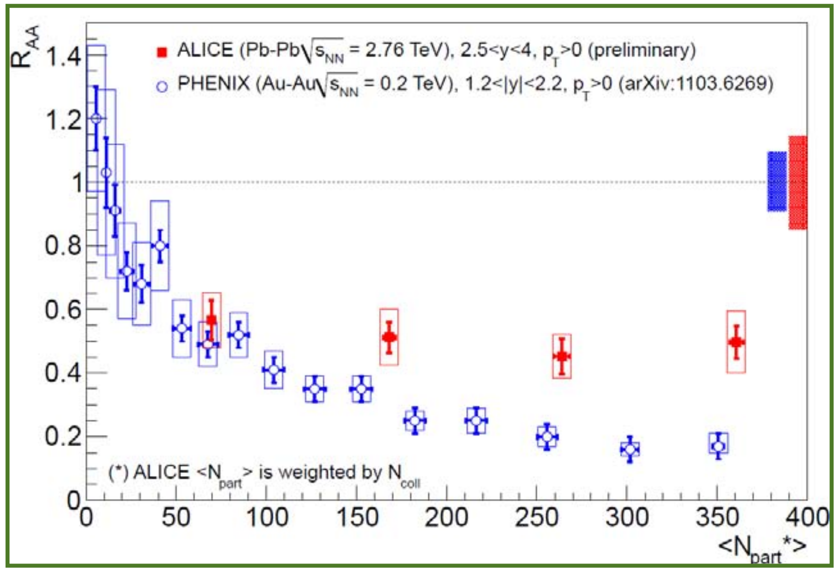
Herzliche Glückwünsche, Helmut!

Starting Point : R_{AA}









The J/ψ story: Two decades worth of data

Modest theory advancement

Lots of ad-hoc phenomenological modeling

It is difficult to unambiguously interpret - we are still not there

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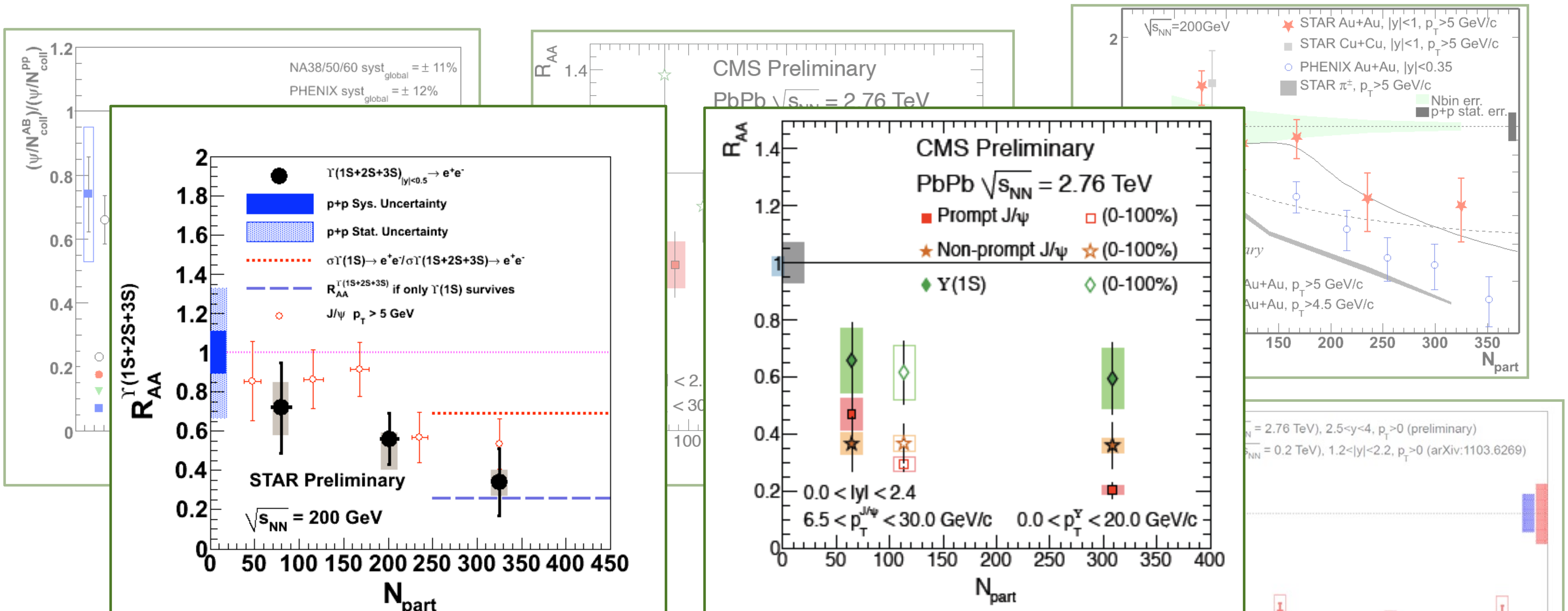

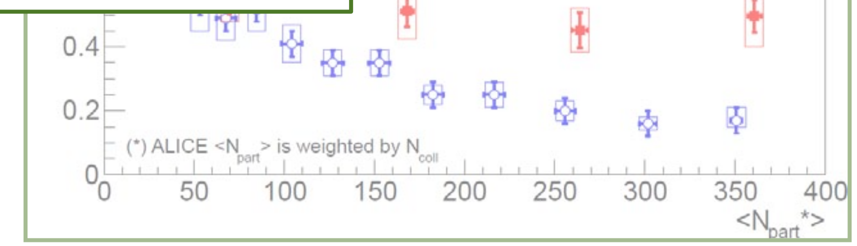

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The Υ story just started !

Main Outline

- What we know theoretically about quarkonium in deconfined medium

- Bridging between theory and experimental data

- Some cross-checks: in attempt to isolate pure hot medium effects

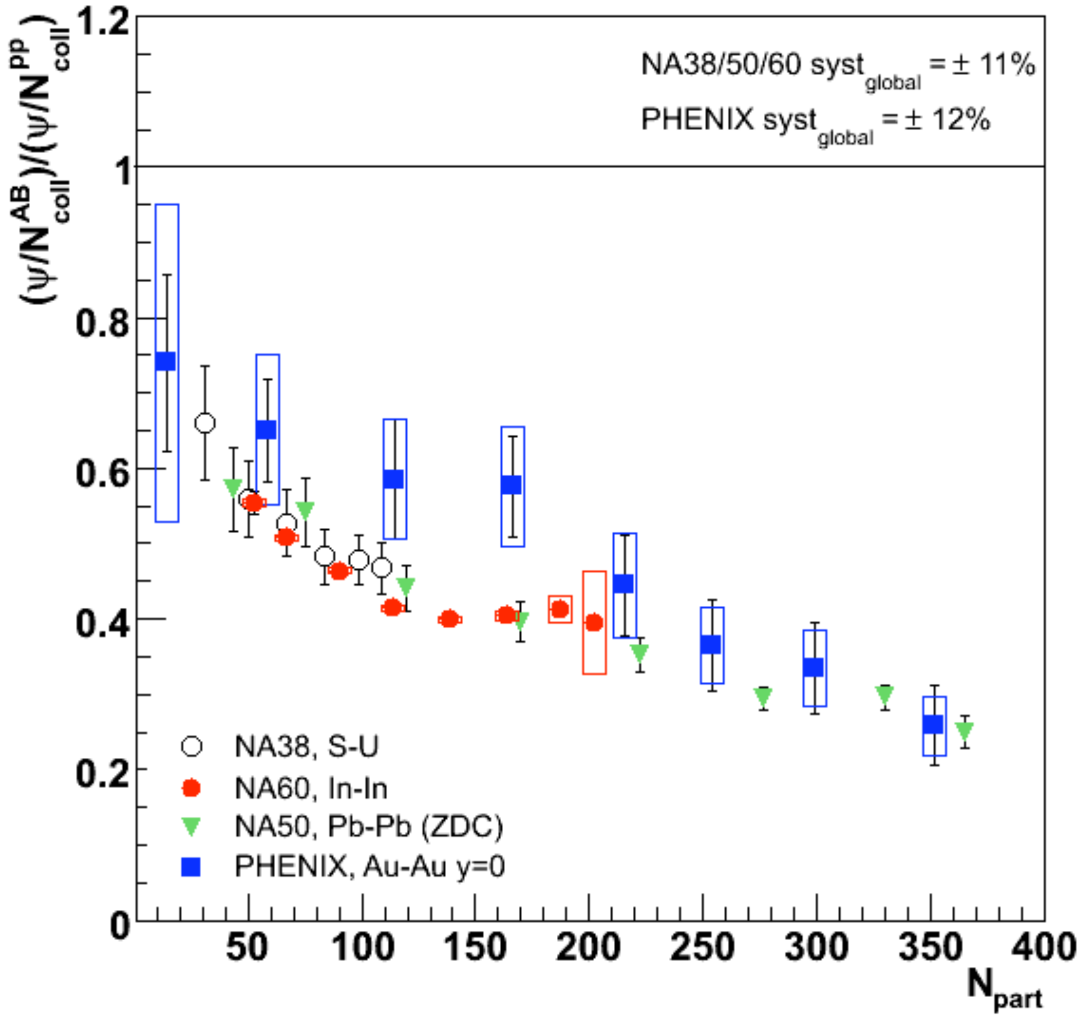
The R_{AA}

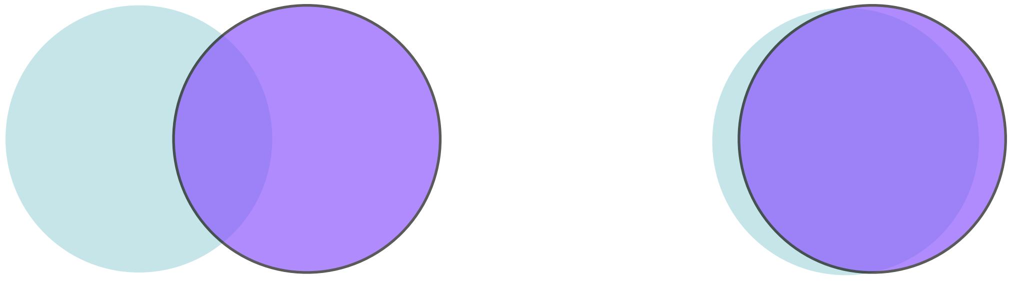
- J/ψ nuclear modification factor:
  yield in AA collisions relative to yield in pp (where no QGP formation expected) scaled with number of binary NN collisions

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- If AA is superposition of pp then R_{AA}=1
- Deviation from 1 indicates medium effects
- If no J/ψ measured then R_{AA}=0

- A J/ψ-suppression pattern observed at SPS and RHIC and LHC





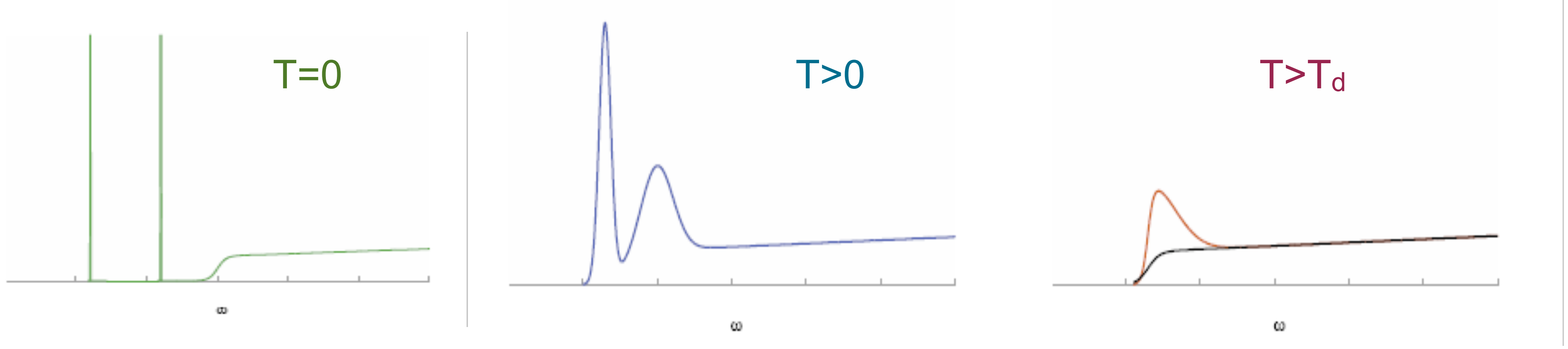
QCD Expectations

- QCD predicts: quarkonium states disappear in the deconfined medium due to temperature effects present: *screening, Landau damping, ...*

- In-medium properties of quarkonium encoded in spectral functions

$$\sigma(\omega,p,T) = \frac{1}{2\pi}\,\mathrm{Im}\int_{-\infty}^{\infty} dt e^{i\omega t}\int d^3x e^{ipx}\langle[J(x,t),J(x,0)]\rangle_T$$

Dissolution ("melting") seen as progressive broadening and disappearance of bound-state peaks

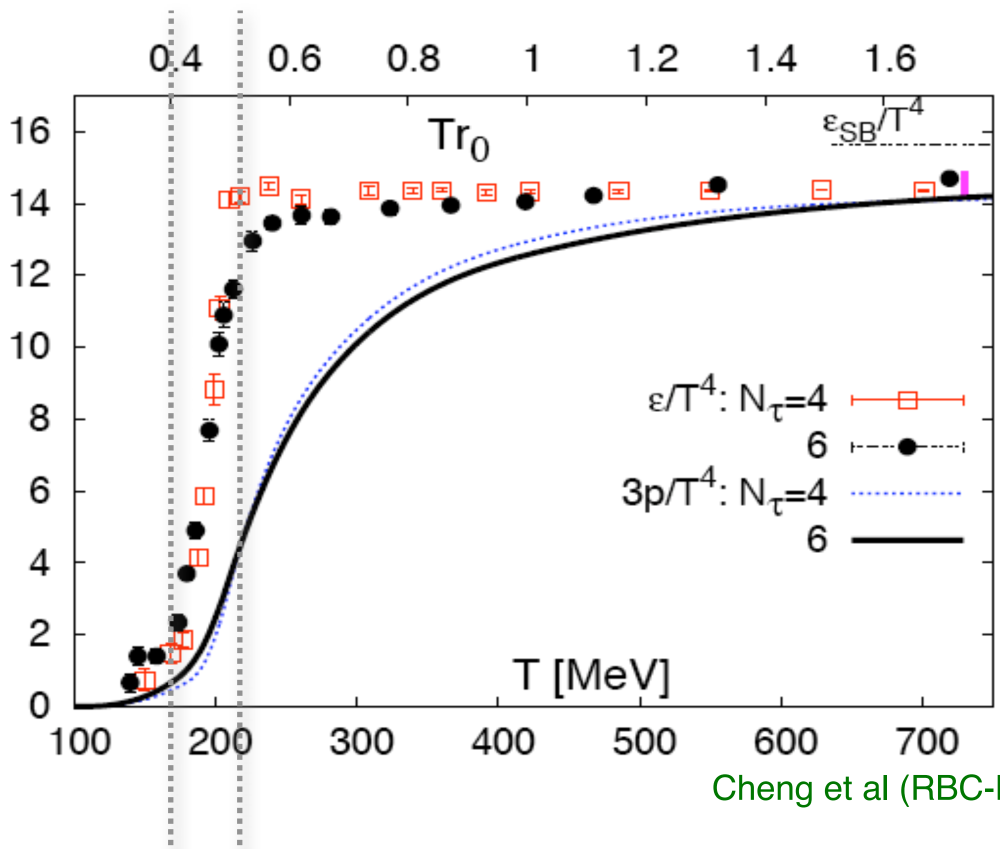


- Theory predicts the J/ψ disappears in the plasma ⟶ J/ψ suppression proposed signal of deconfined QGP

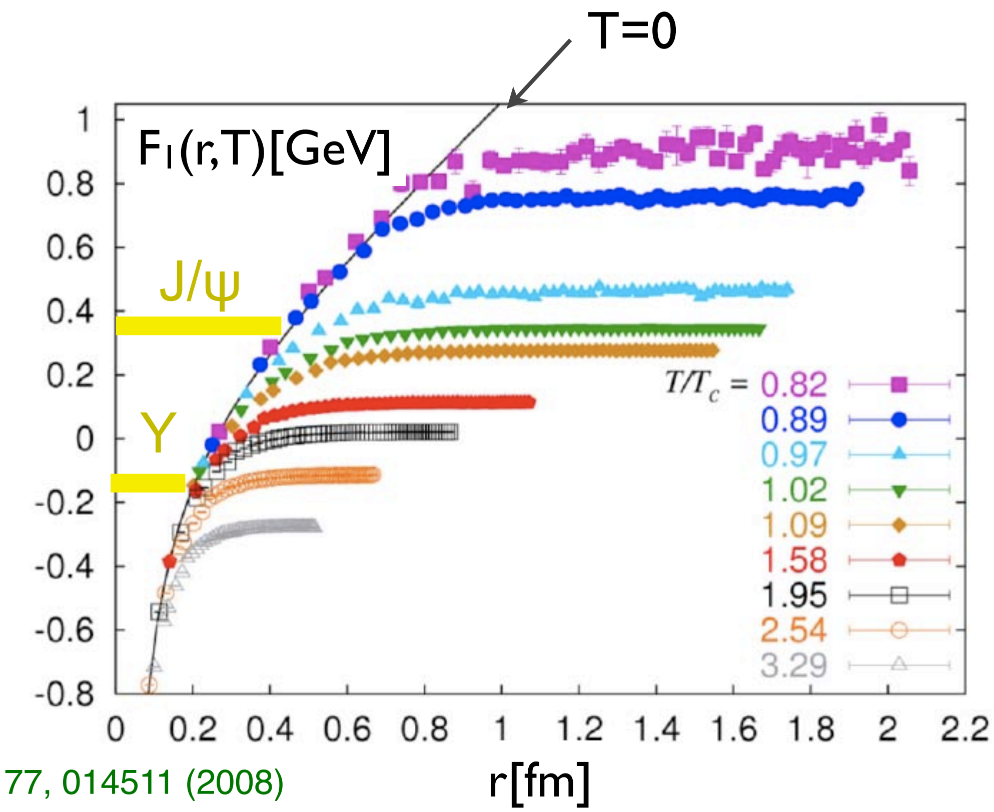
Matsui, Satz PLB 1986

What Do We Know Now

Deconfinement



Color screening



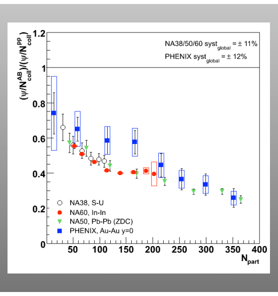
Cheng et al (RBC-Bielefeld) PRD 77, 014511 (2008)

- Rapid rise of the energy density: liberation of new degrees of freedom
- Deconfinement seen on lattice

- Strong screening of static Q-Qbar free energy - sets in at shorter distances with increasing T

  $r_{scr} < r_{J/\psi}$ "melting" of the J/ψ

What's the Physics Behind



But is the J/ψ R_{AA} a signal for deconfinement and screening ?!

To answer this question we need to know:

- How the properties of J/ψ change in a deconfined medium
  Determine the spectral function

- Relate an equilibrium spectral function to R_{AA}
  Through real-time dynamics

- Identify what physics might contribute to R_{AA}
  for example: Suppression is seen in pA, dA data as well
  (where no QGP formation expected)
  Cold nuclear matter effects - could be relevant to AA

Theory Progress

- Lattice QCD, potential models, effective field theories (EFT)

- Spectral functions are calculated   Cabrera, Rapp, Mócsy, Petreczky, Alberico, Beraudo, ...

- Potential model assumes most medium effects on quarkonium properties can be described by a T-dependent potential

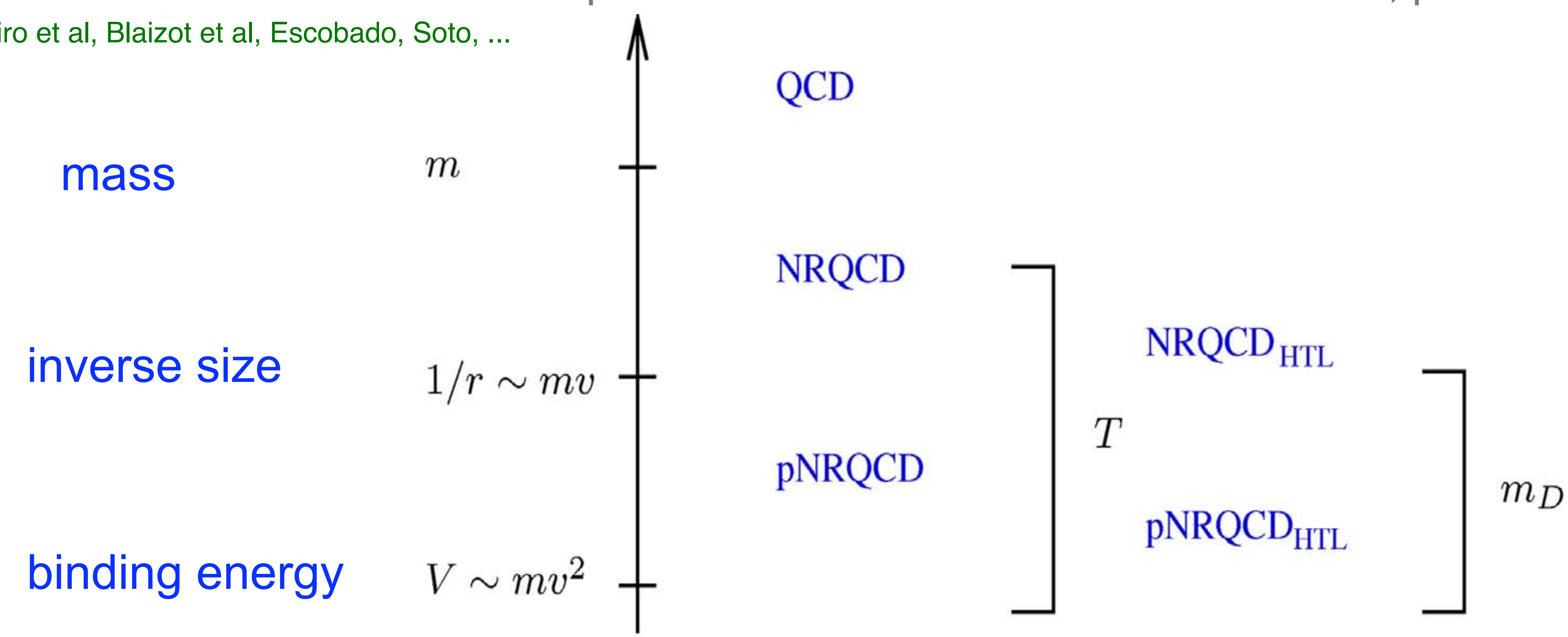
rue when E_{bin} is the smallest scale

- Recently: Potential model (can be placed on more solid grounds) appears as the tree-level approximation of the EFT and can be systematically improved

The heavy quark mass provides a hierarchy of different energy scales

Scale separation allows to construct sequence of effective field theories: NRQCD, pNRQCD

Laine et al, Vairo et al, Blaizot et al, Escobado, Soto, ...



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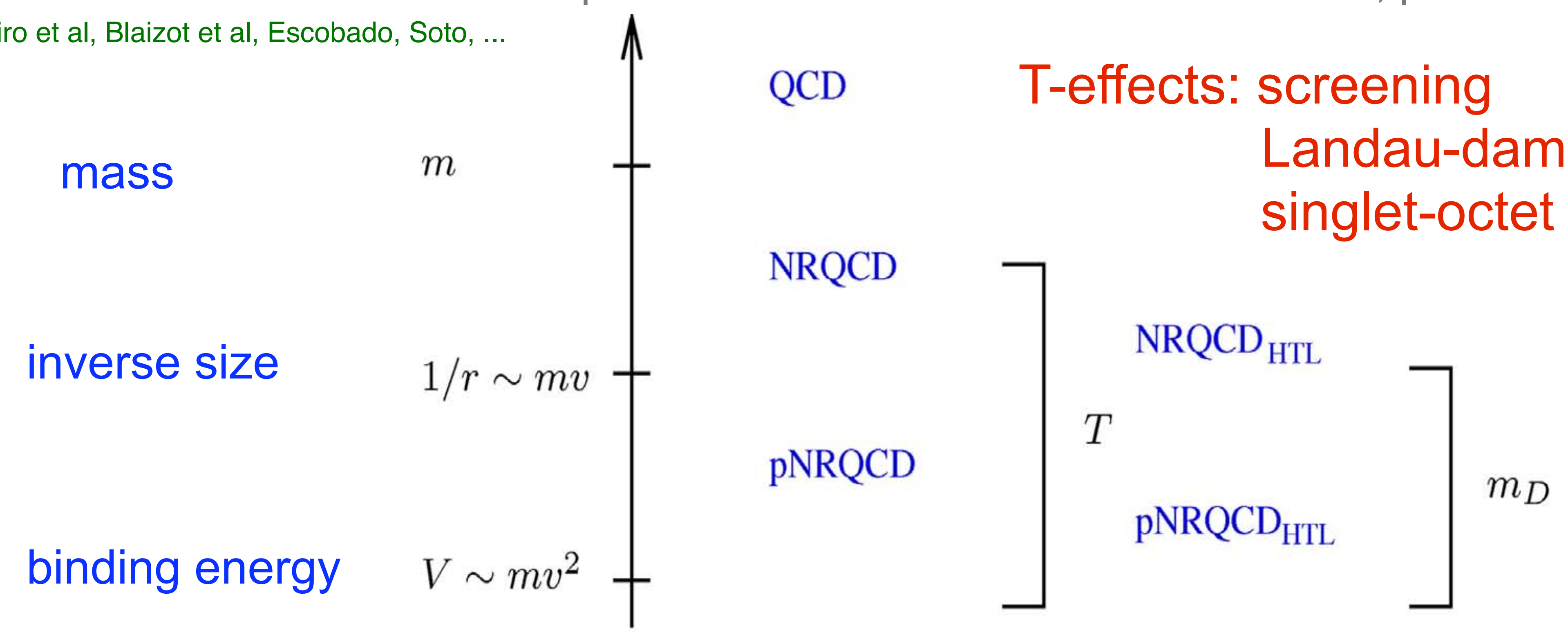


T-effects: screening
Landau-damping
singlet-octet transition

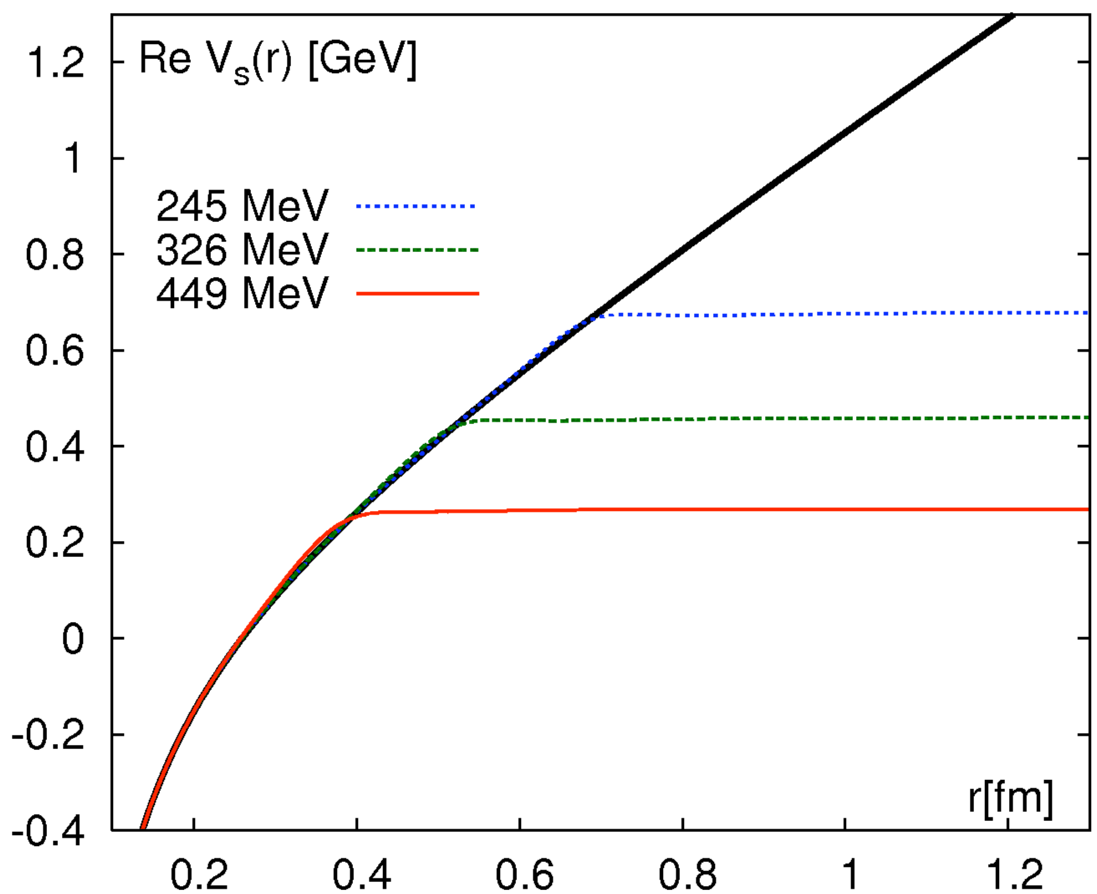
The Complex Potential

Thermal contributions come from Re (→ binding energy) and Im (→ width) part

Constrain Re$V_s(r)$ by lattice QCD data on the singlet free energy

Take Im$V_s(r)$ from pQCD calculations

Maximal value



Mócsy, Petreczky, PRL 99 (07) 211602

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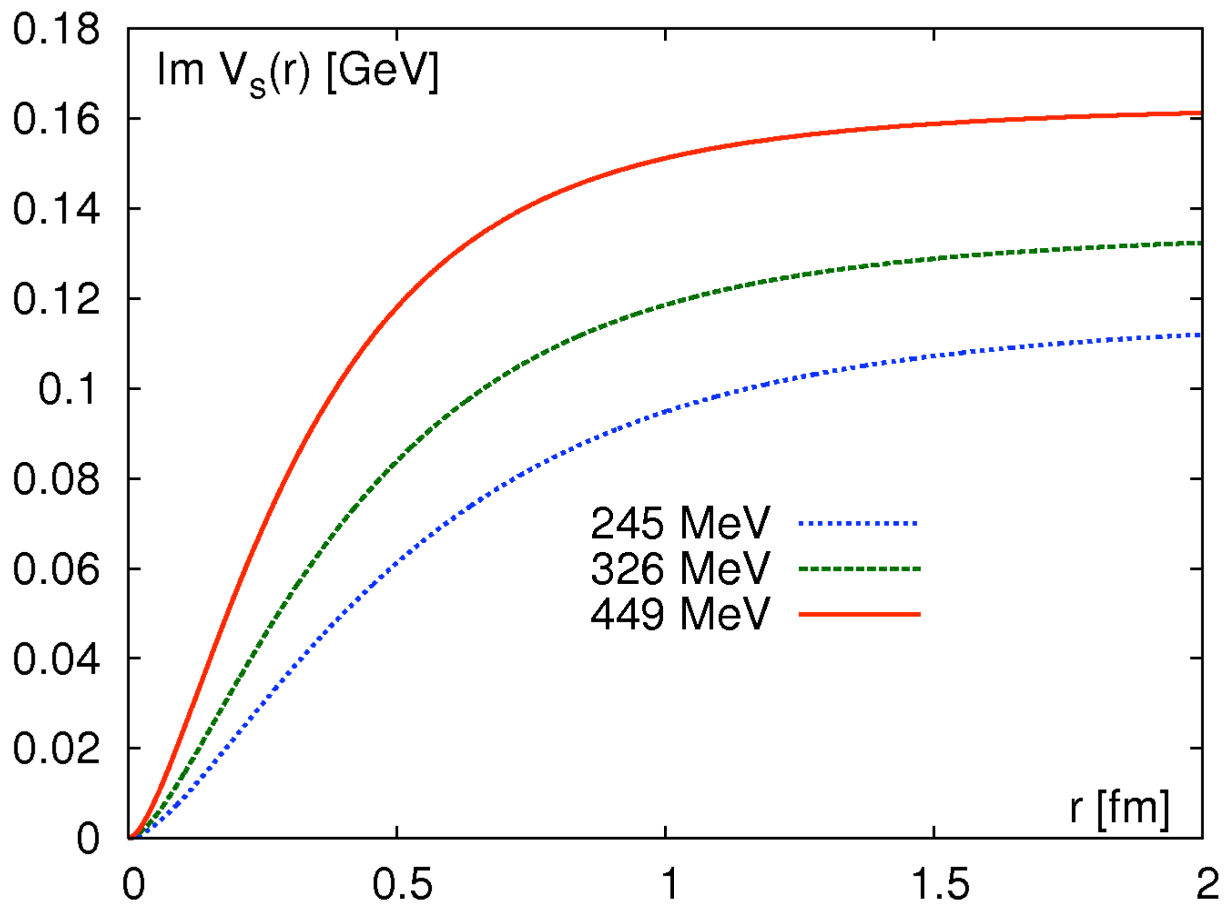

Burnier, Laine, Vepsalainen JHEP 0801 (08) 043
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Study the effect of color screening and of dissipation on the quarkonium spectral functions.

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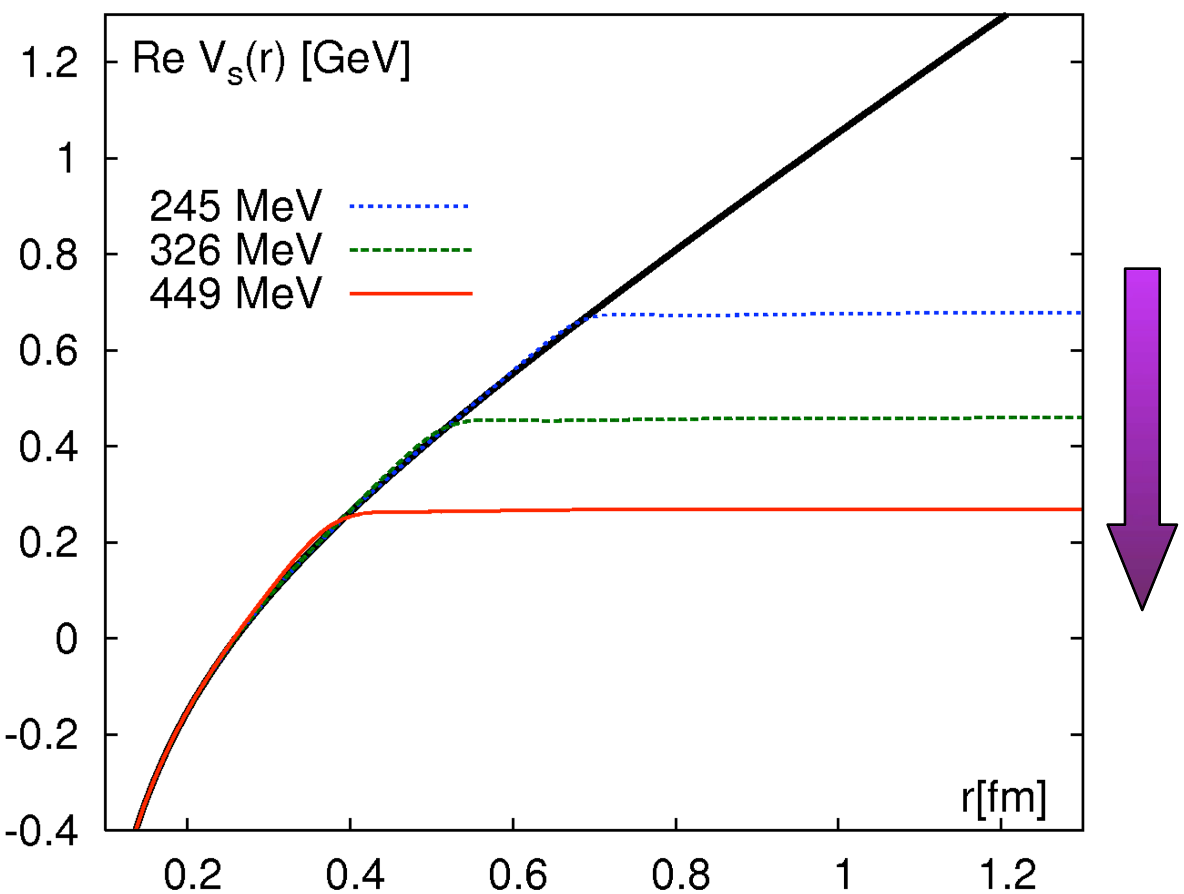

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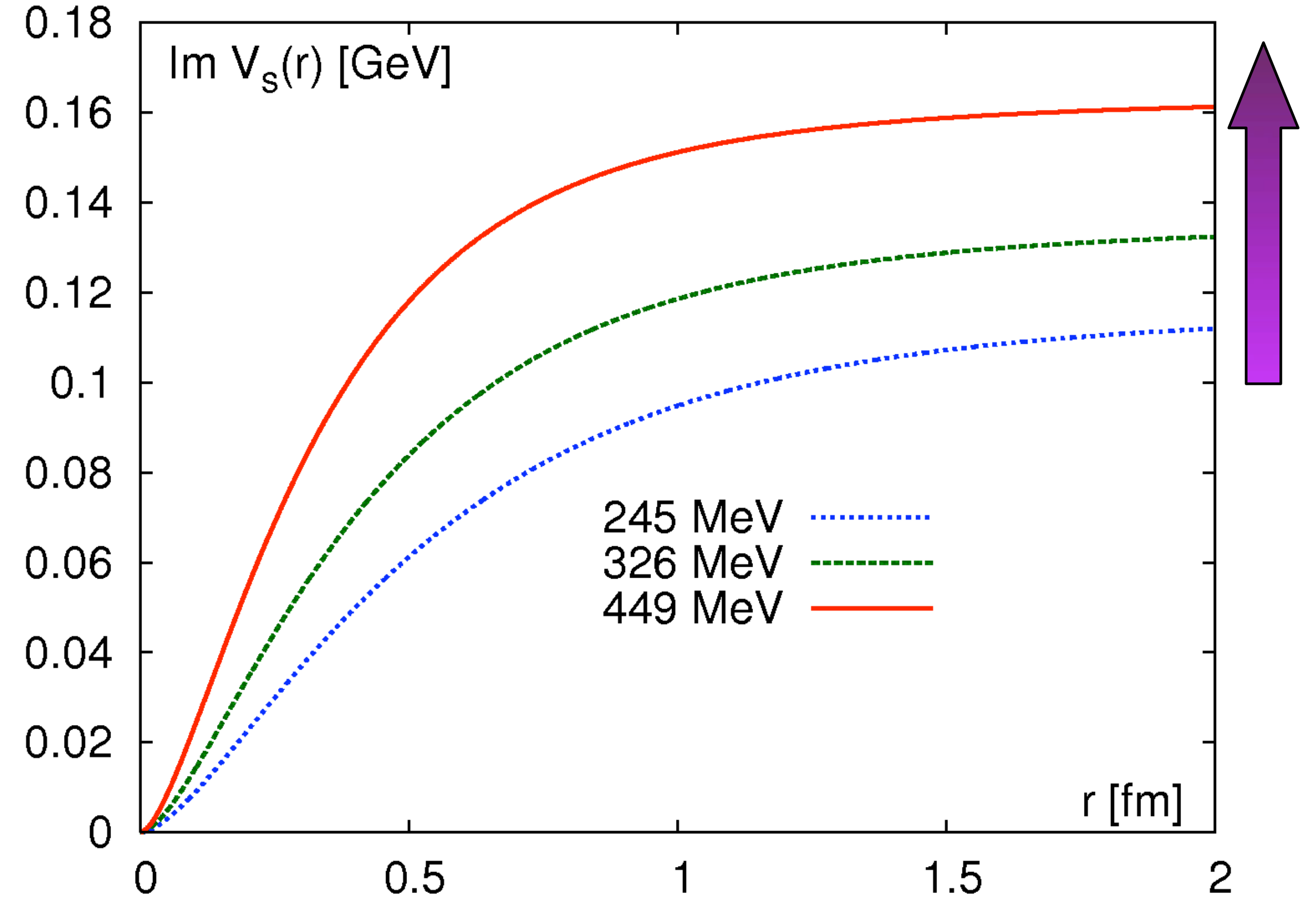

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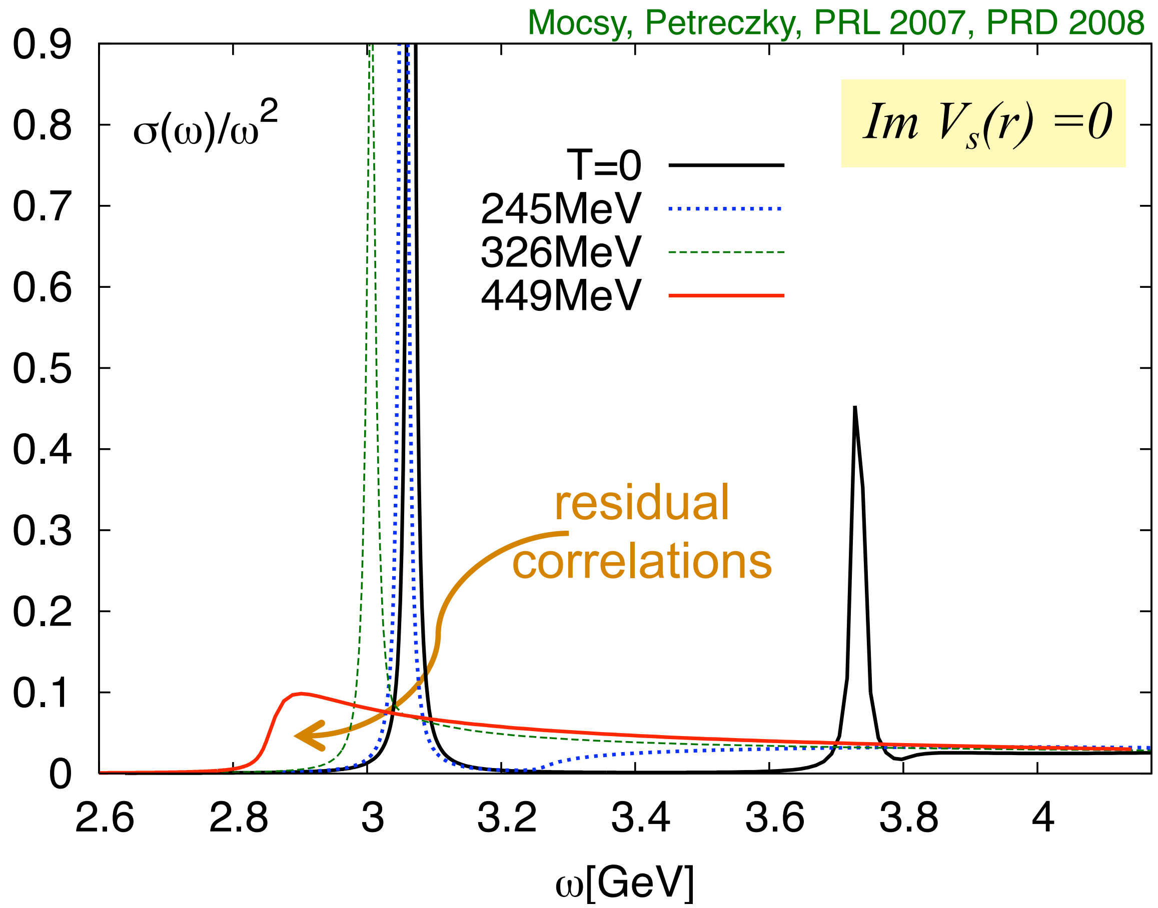
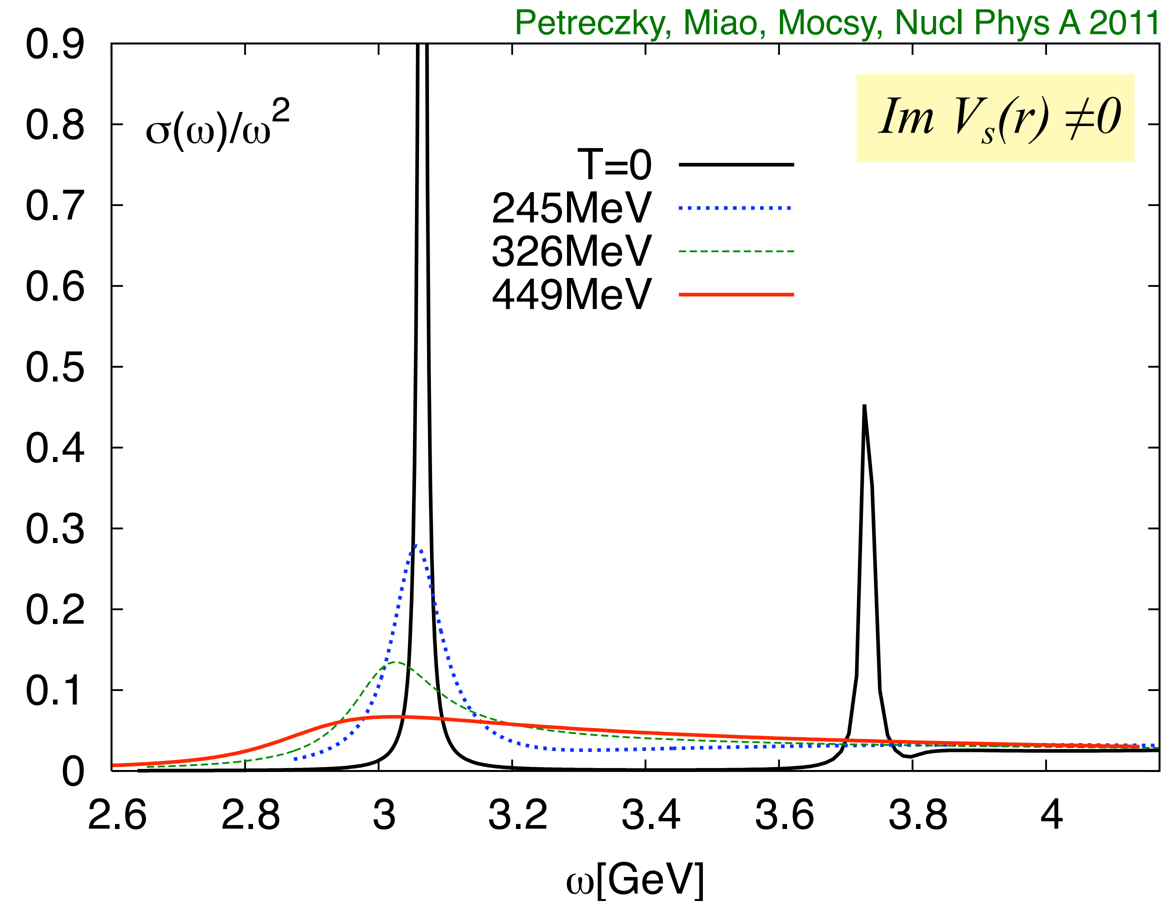
Charmonium Spectral Function

Calculated in full QCD

Take the upper limit for the real part of the potential allowed by lattice calculations

Take the perturbative imaginary part of the potential and the code from Burnier, Laine, Vepsalainen JHEP 0801 (08) 043





- 1S peak there with binding energy reduced
- residual c-cbar correlations persist

threshold enhancement

- agrees with Cabrera, Rapp , PRD 2007

- dramatic changes with Im part, peaks become very broad
- agrees with Mocsy, Petreczky, PRL 2007

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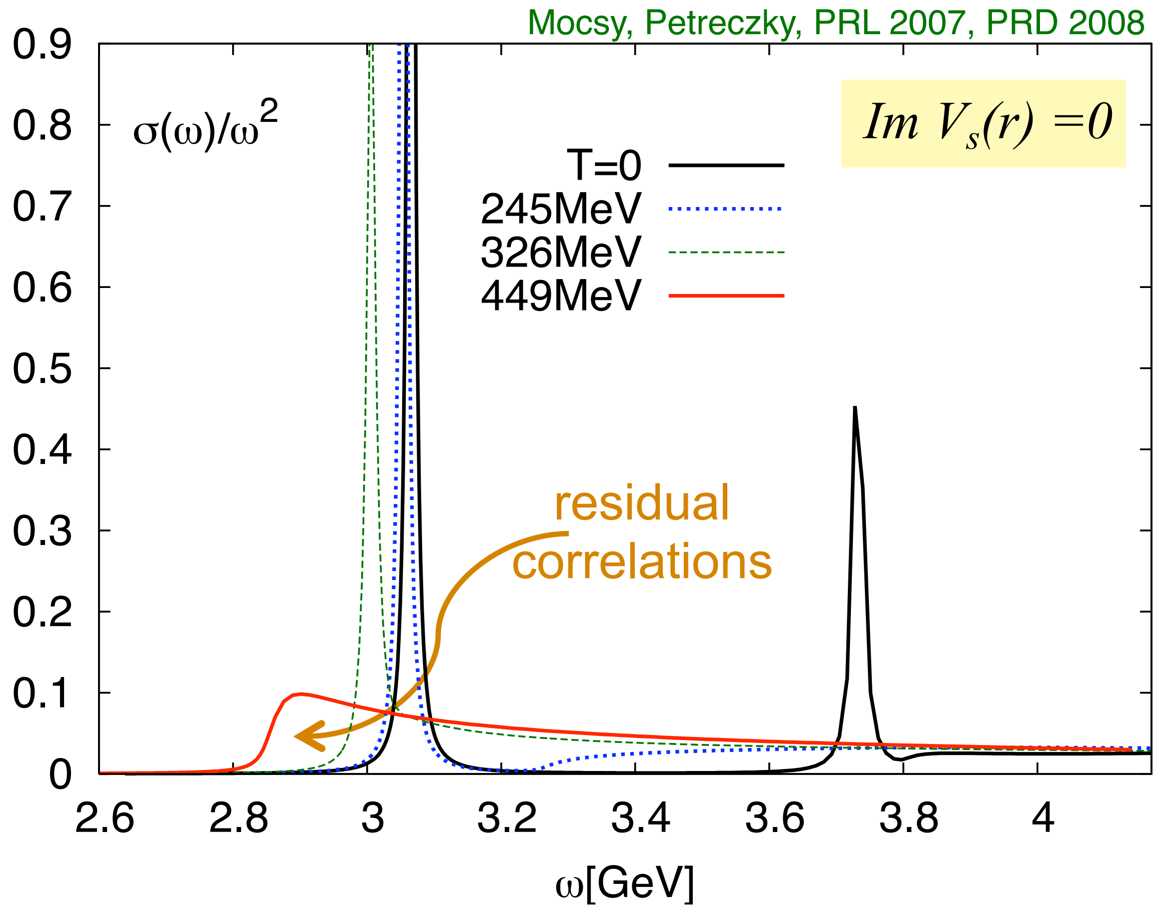

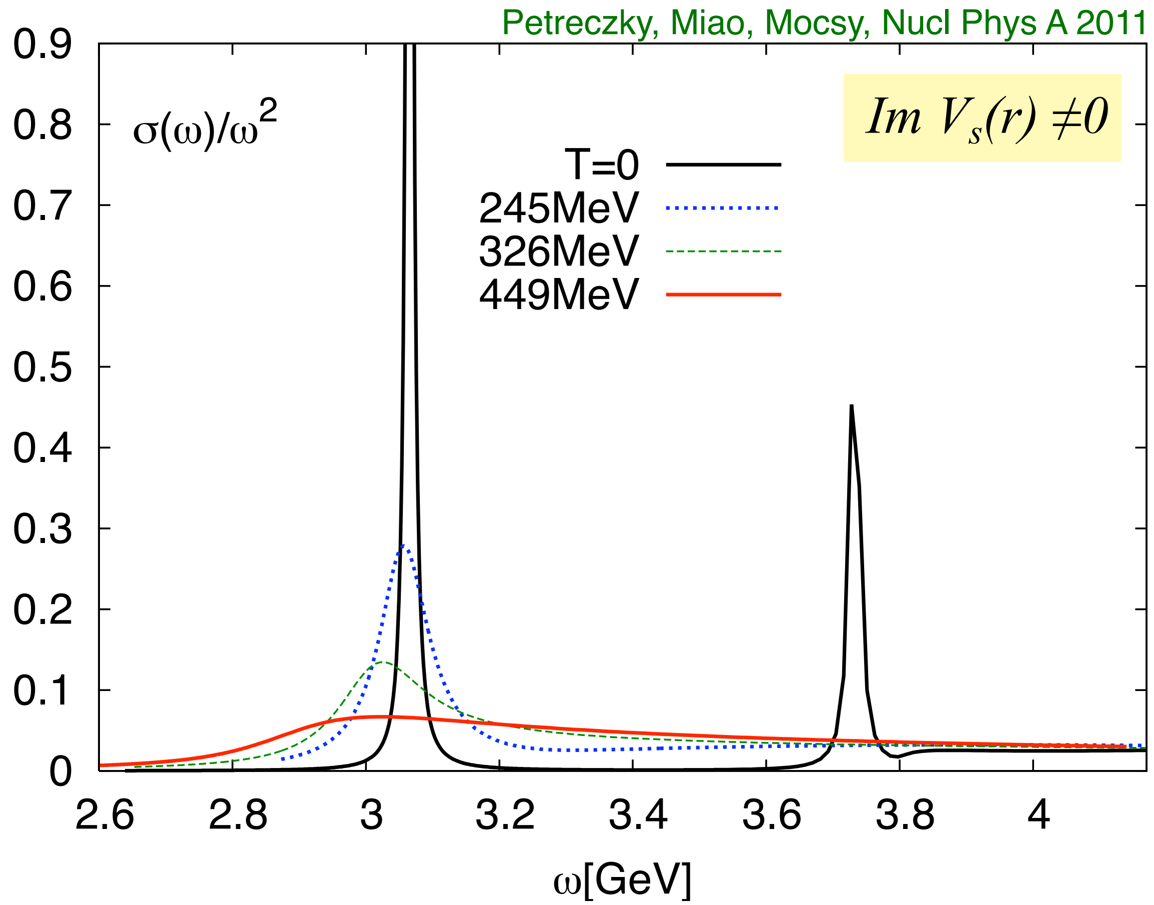

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- agrees with Cabrera, Rapp , PRD 2007

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No charmonium state could survive for *T > 240* MeV

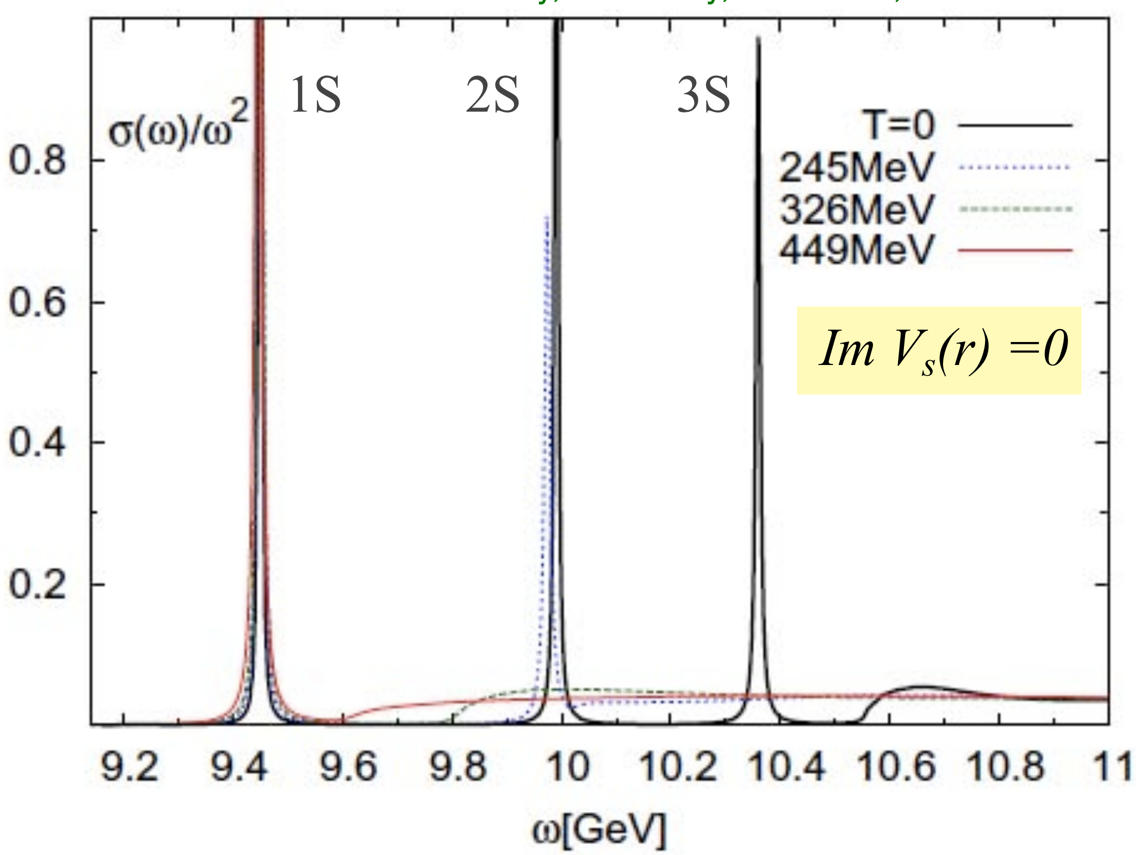
Bottomonium Spectral Function

Calculated in full QCD

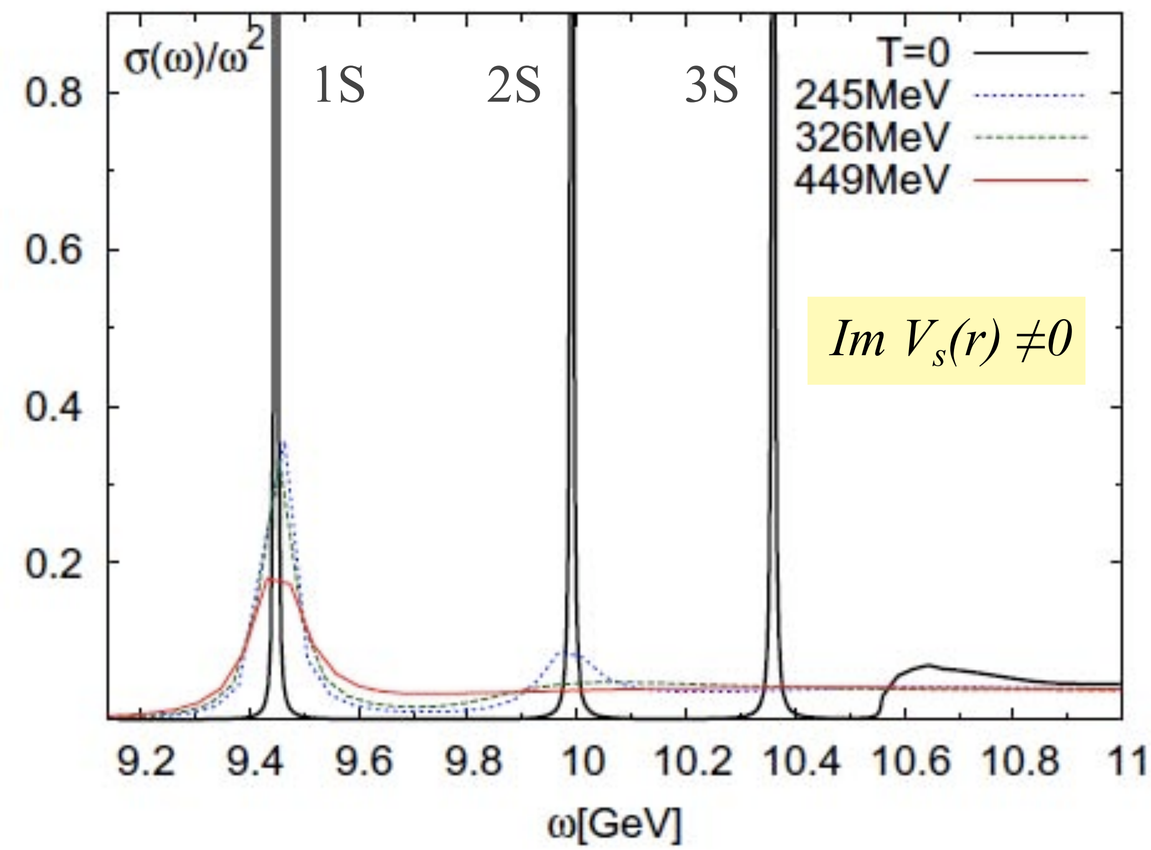
Take the upper limit for the real part of the potential allowed by lattice calculations

Take the perturbative imaginary part of the potential and the code from Burnier, Laine, Vepsalainen JHEP 0801 (08) 043

Mocsy, Petreczky, PRL 2007, PRD 2008



Petreczky, Miao, Mocsy, Nucl Phys A 2011



- 1S peak and remnant of 2S state there
- binding energies reduced
- Threshold enhancement

- dramatic changes with Im part
  peaks significantly broaden

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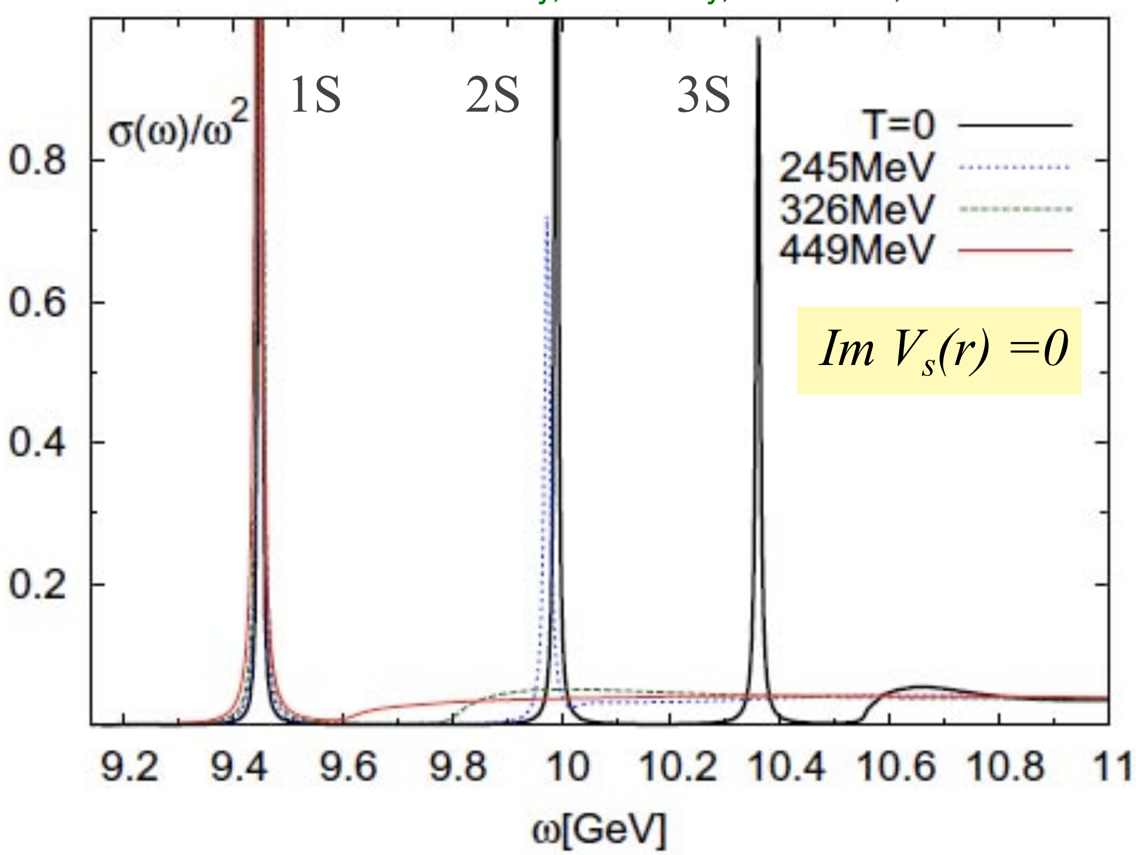

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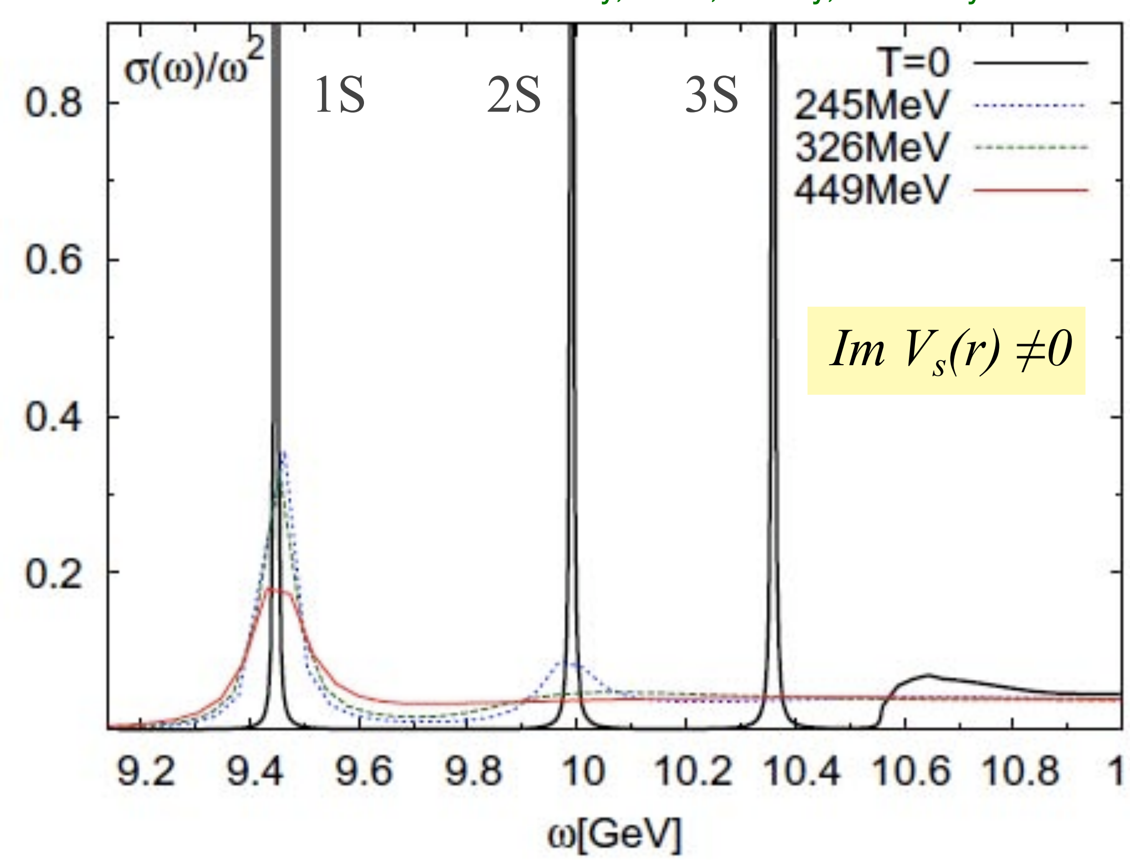

- 1S peak and remnant of 2S state there
- binding energies reduced
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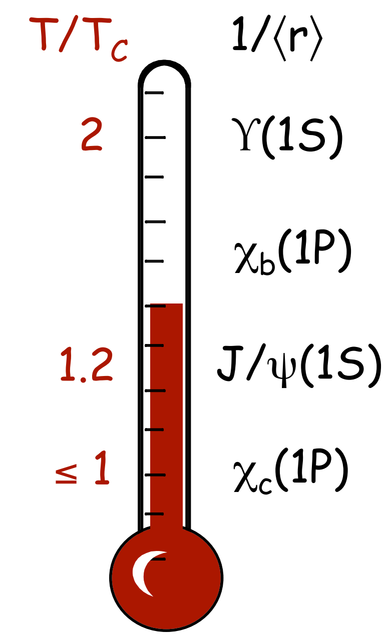
No bottomonium state could survive for $T > 450$ MeV

Thermometer

- Quantitative estimates of peak disappearance
  Thermometer of upper limits T_{diss}



Note: E_{bin} would be smaller with other potentials

Charmonium sensitive to ReV

Bottomonium sensitive to Im V

Could be different mechanism behind melting J/ψ and Y

- Be aware of the meaning of T_c !

In quenched QCD $T_c = 270$ MeV

Boyd et al 1996

In full QCD there is $T_{chiral} \cong 157$ MeV and $T_{onset\ of\ screening} \cong 190$ MeV

Budapest-Wuppertal 2010, HotQCD 2011 Bazavov, Petreczky, 2010

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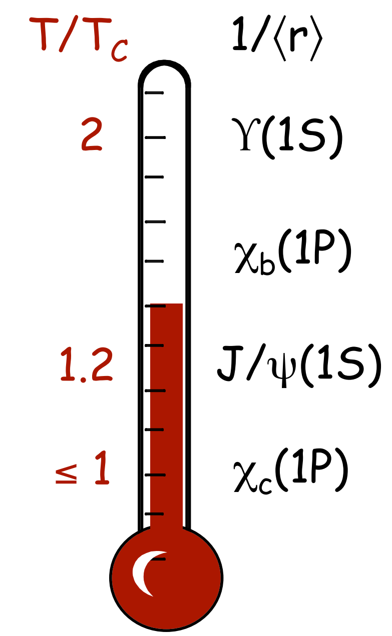

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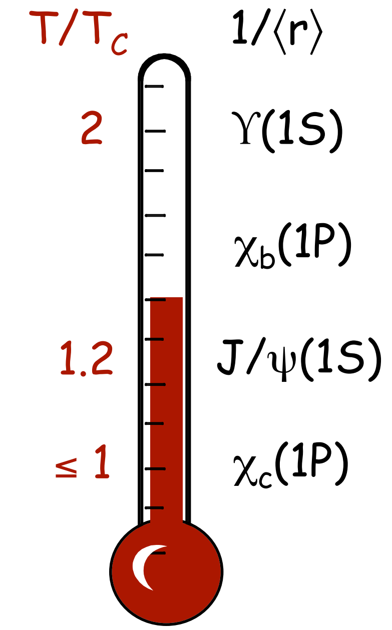

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- While there is a hierarchy in the "melting" temperatures this does not clearly imply a sequential suppression pattern

Ex: a correlated b-bbar pair can become a 1S or a 2S state

“Lattice says so ... “

- *Ugly rumor : “Lattice tells J/ψ survives to $2T_c$”*

There is no evidence for that.

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Correlator ratios not sensitive to spectral function changes.

- We can calculate the Euclidean correlator
  quantity also calculated on the lattice

$$\frac{G(\tau,T)=\int\sigma(\omega,T)K(\tau,\omega,T)d\omega}{G_{rec}(\tau,T)=\int\sigma(\omega,T=0)K(\tau,\omega,T)d\omega}$$

- Correlators do not change
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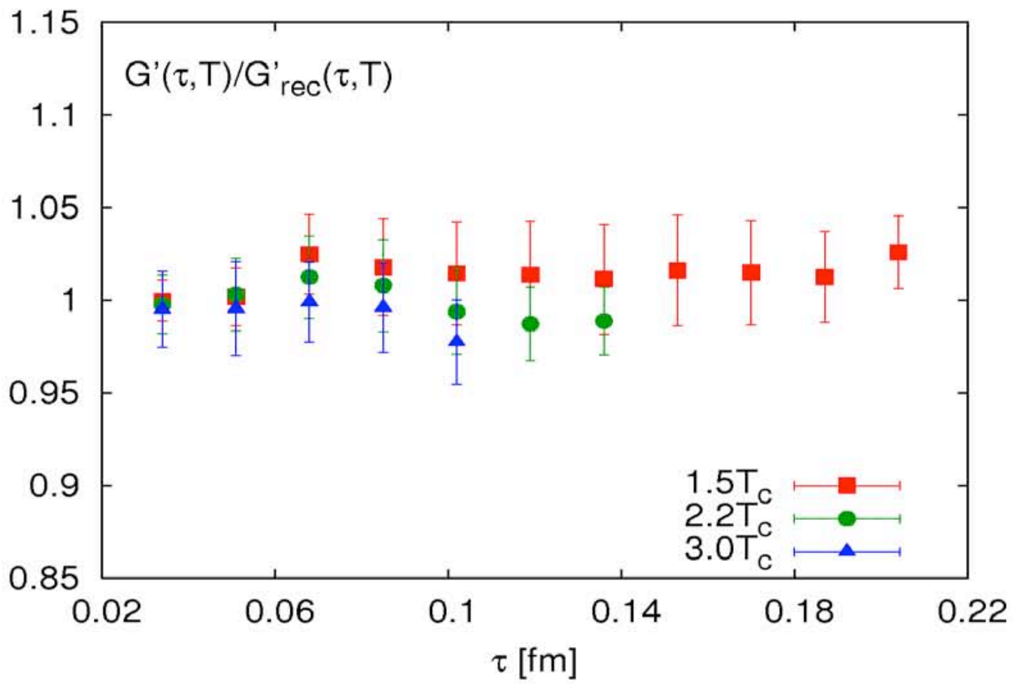
- We now understand that changes come
  from zero modes



Datta et al; Jakovac et al; Umeda; Petreczky, 2005-2009

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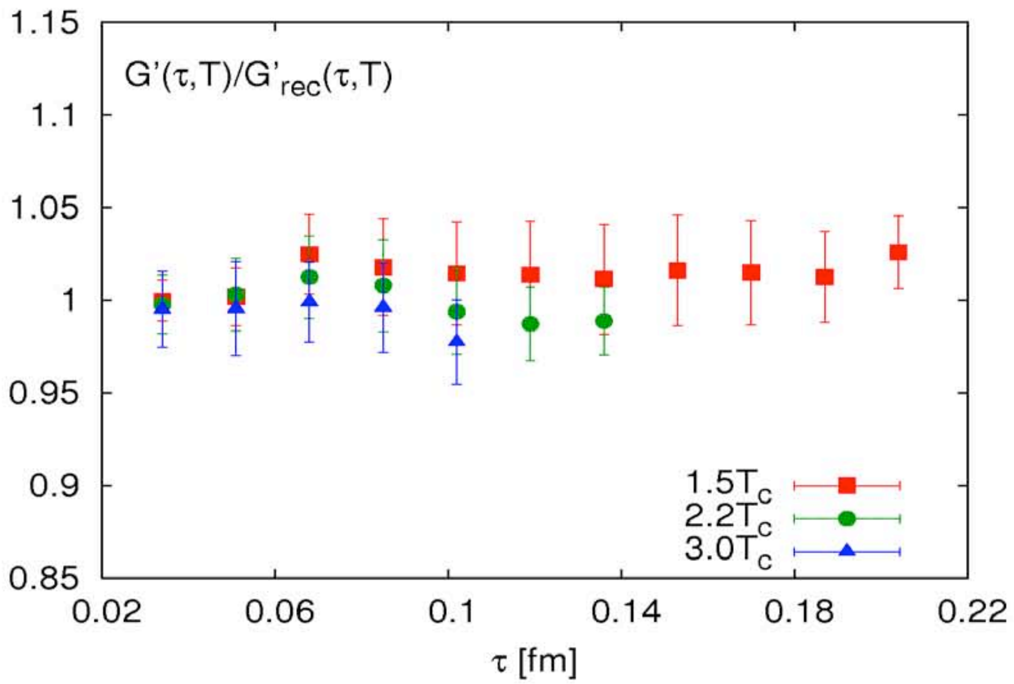

Datta et al; Jakovac et al; Umeda; Petreczky, 2005-2009

+ Lattice spectral functions do not suggest J/ψ survival

Charmonium Spectral Function

Extracted in quenched QCD

Extracted from correlation function of mesonic currents in Euclidean time

$$G(\tau,T) = \int \sigma(\omega,T)K(\tau,\omega,T)d\omega$$

correlator
directly calculated

spectral function extracted
not directly calculated

$\mathcal{O}(10)$ data but $\mathcal{O}(100)$ degrees of freedom to reconstruct

$G(\tau,T)$ → MEM → $\sigma(\omega,T)$

maximizes the conditional probability of having the spf given the data and some prior knowledge

Umeda et al, EPJ C39S1 (05) 9, Asakawa, Hatsuda,PRL 92 (2004) 01200, Datta et al,PRD 69 (04) 094507,Jakovac et al PRD 2007, ...

Shortcomings: limited # of data points $T = 1/(N_t a)$
limited extent in tau $\tau_{max} = 1/(2T)$
default model dependence *large*

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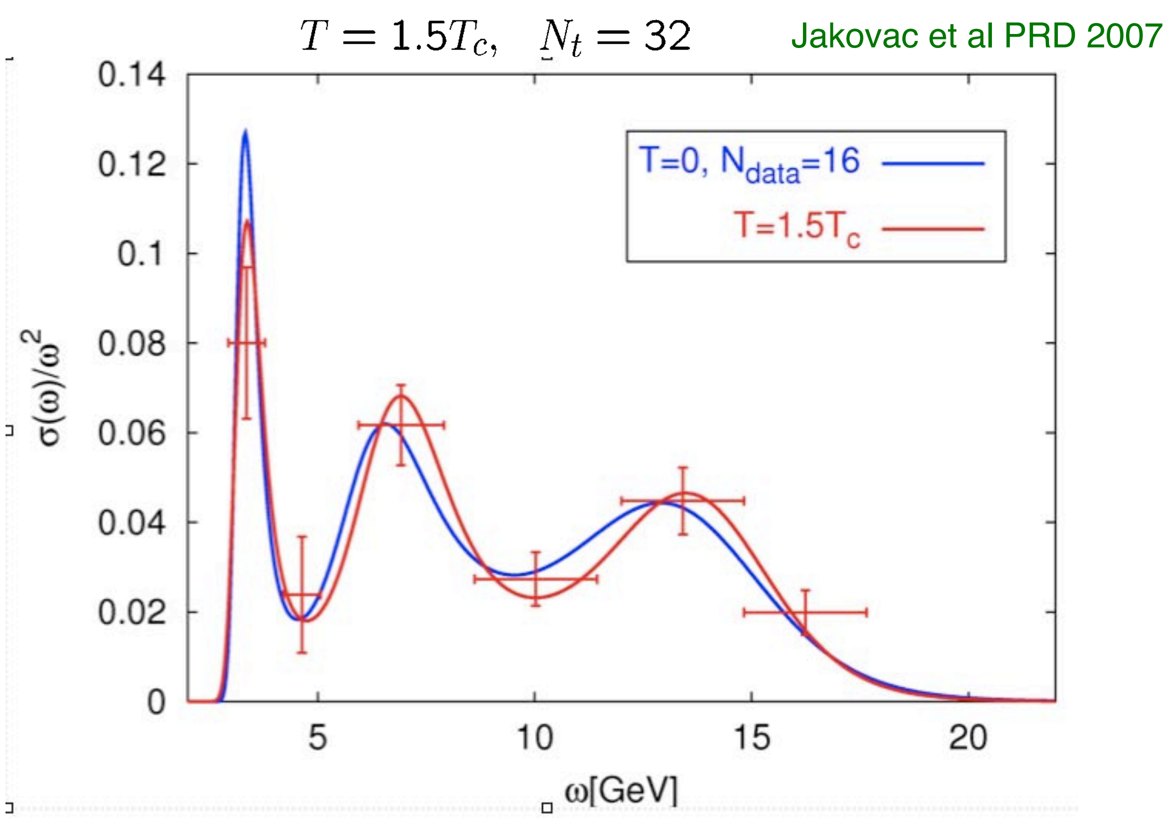

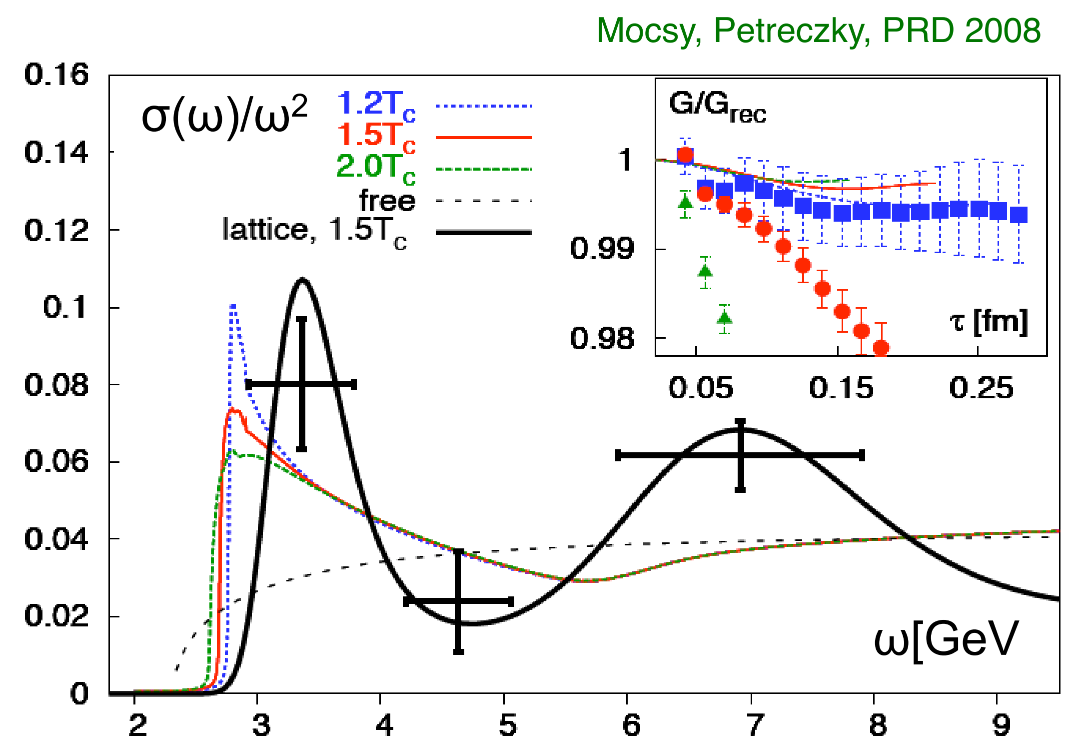

$$T = 1/(N_t a)$$
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1st peak consistent with threshold enhancement

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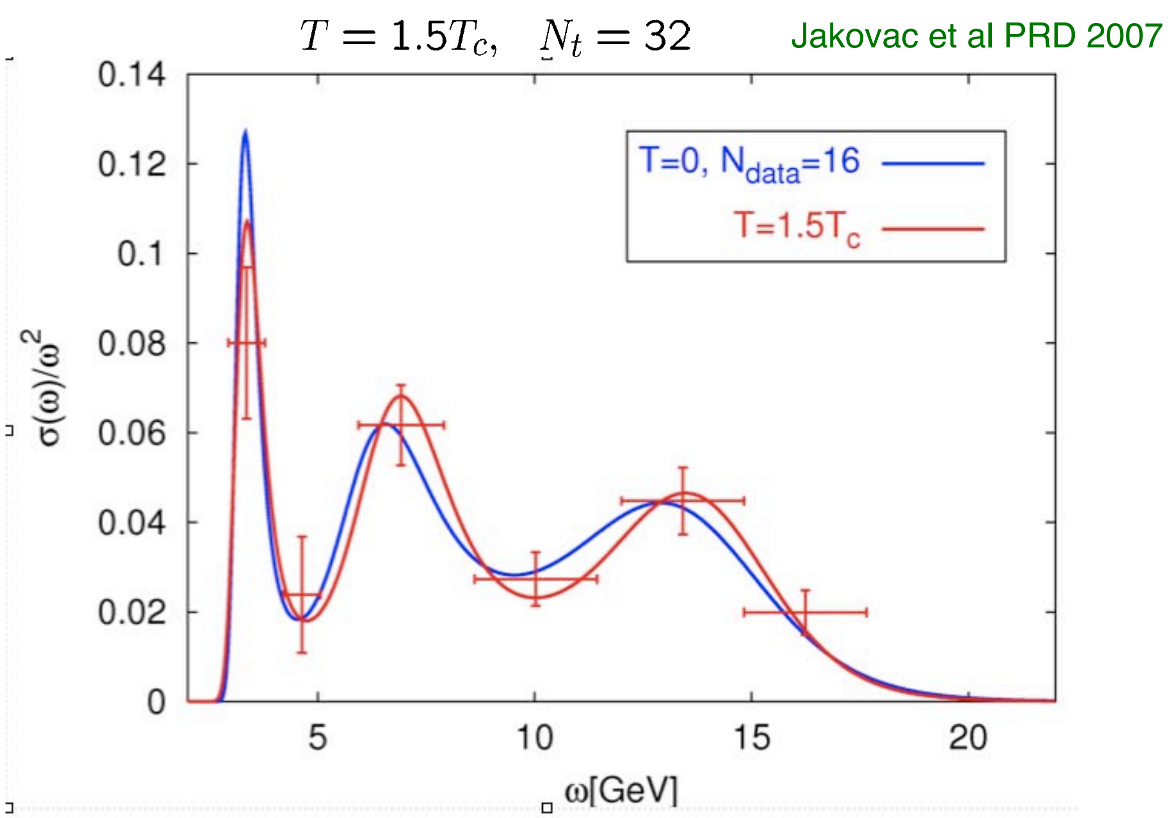

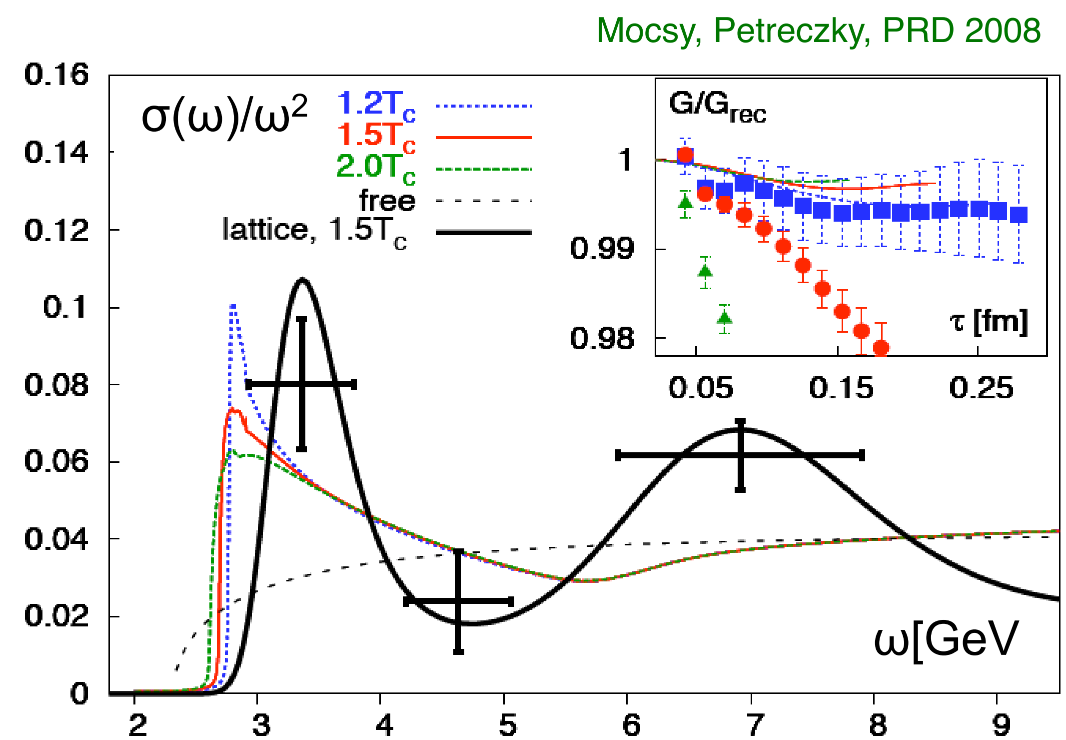

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Comparing low resolution confined phase (blue) to low resolution deconfined phase (red) and getting an agreement does **not** imply the agreement will hold at high resolution

agreement in low resolution does
not imply agreement at high resolution

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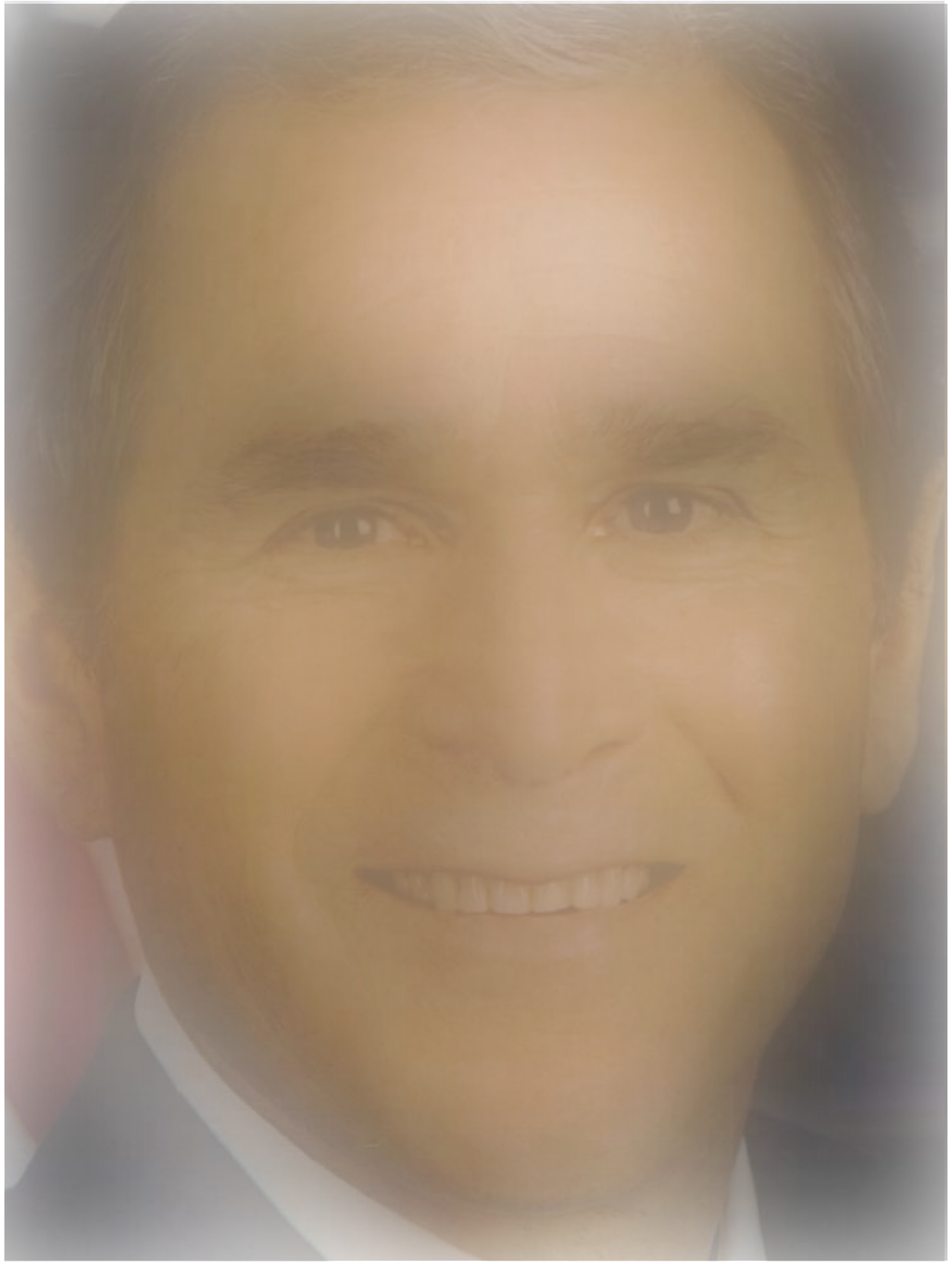

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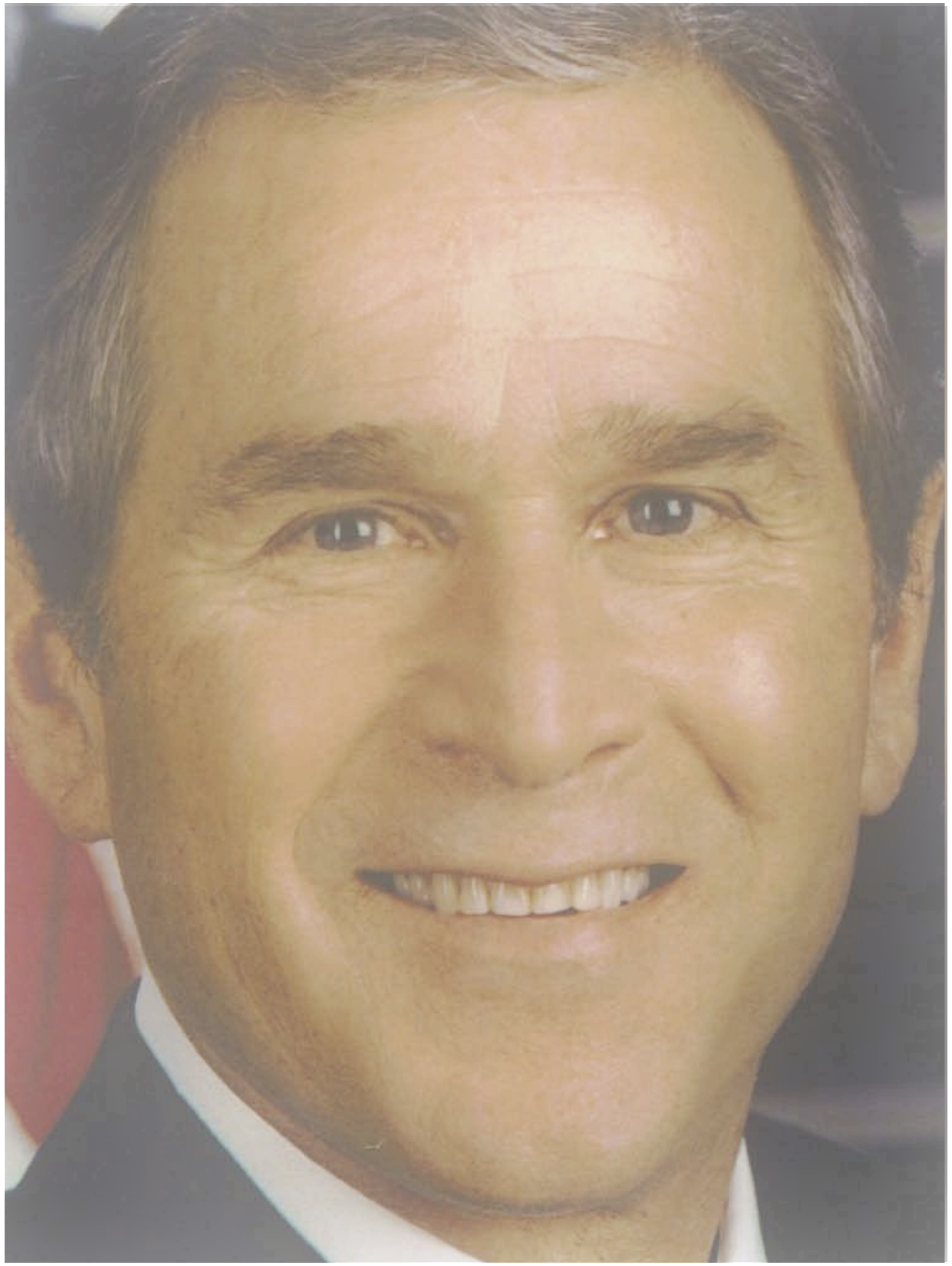

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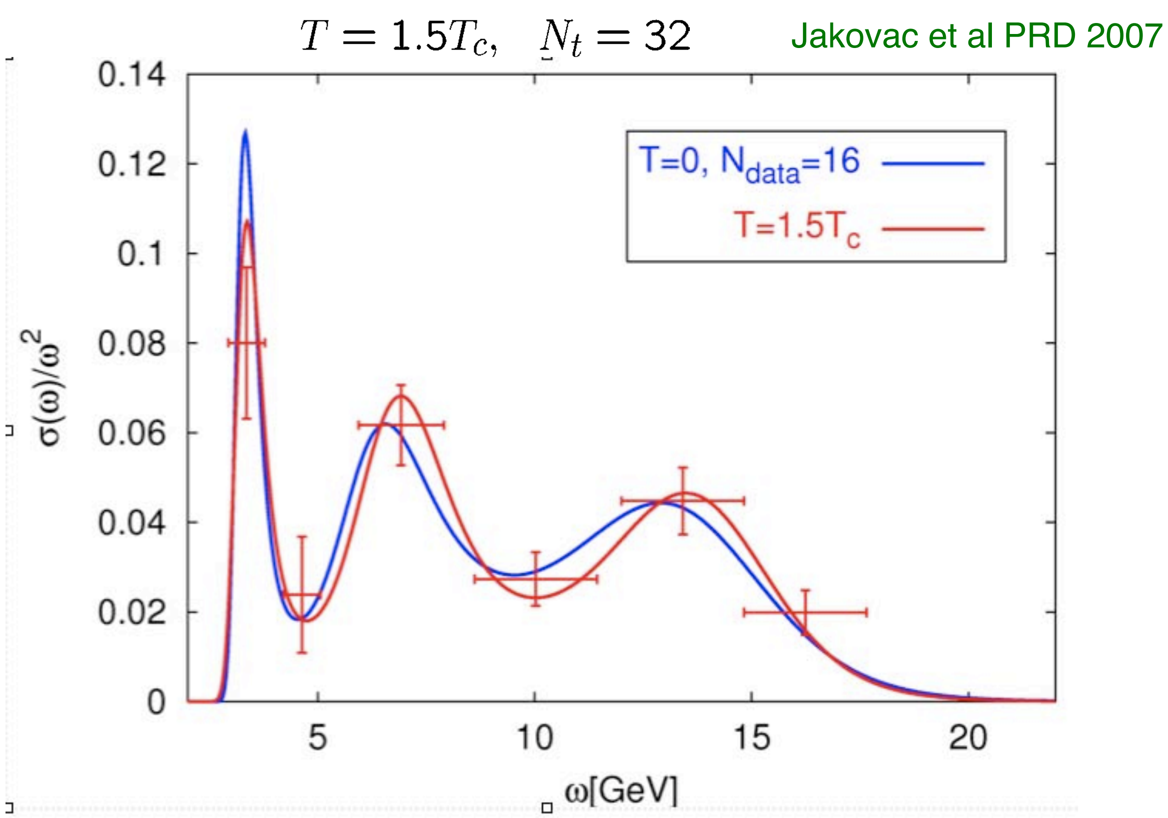
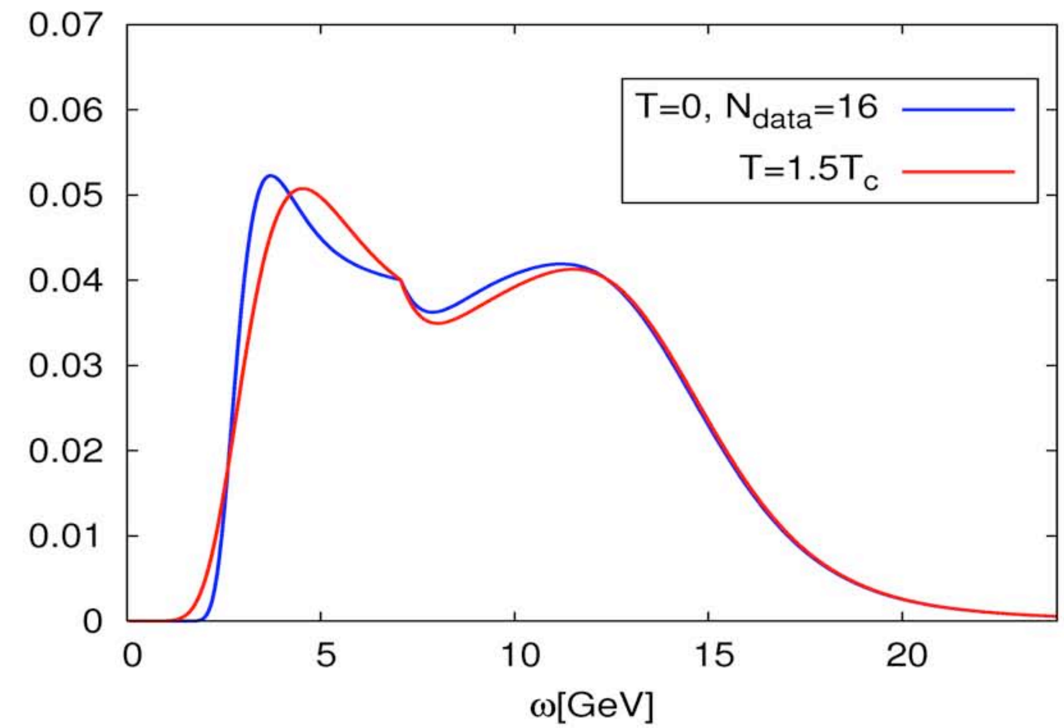


prior: perturbative continuum spf (no lattice effects)



prior: from T=0 data at high energies

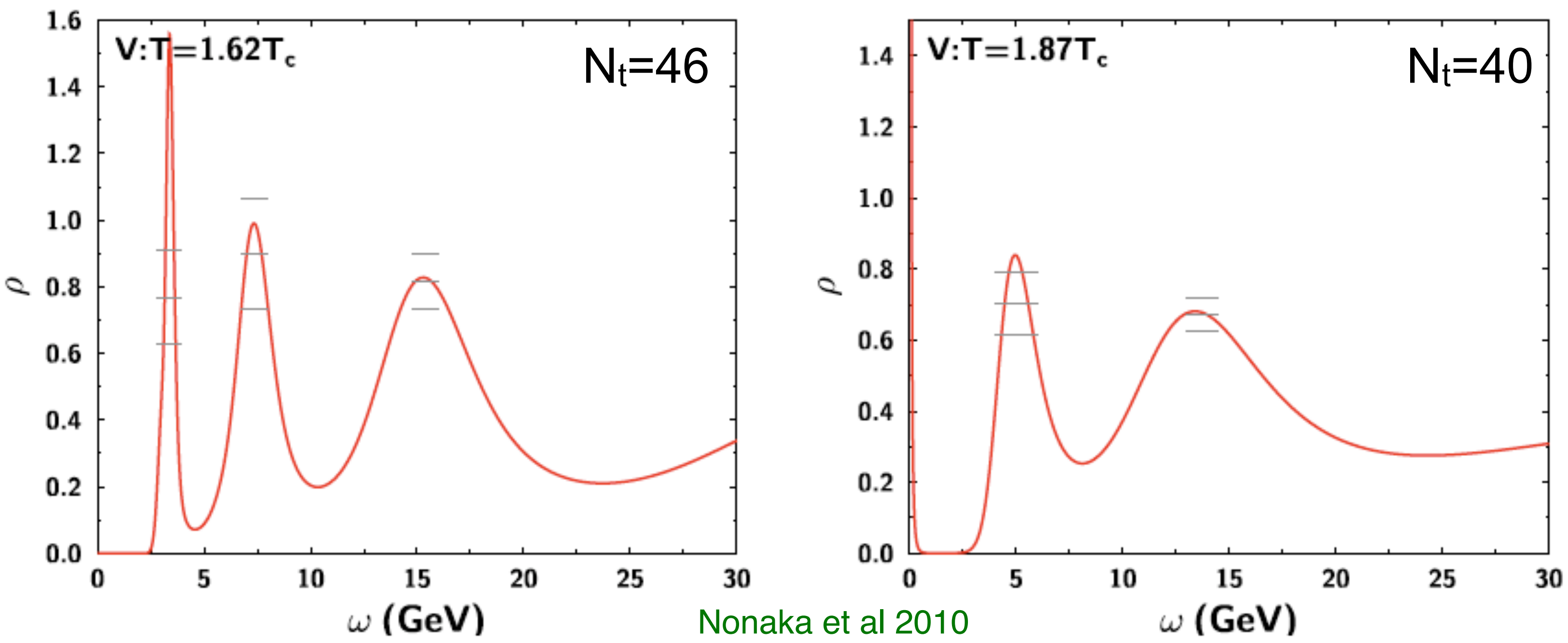
$$T = 1/(N_t a)$$
$$\tau_{max} = 1/(2T)$$

Strong default model dependence
peak - no peak ?!

Charmonium Spectral Function

Extracted in quenched QCD

Most recent lattice results



Nonaka et al 2010

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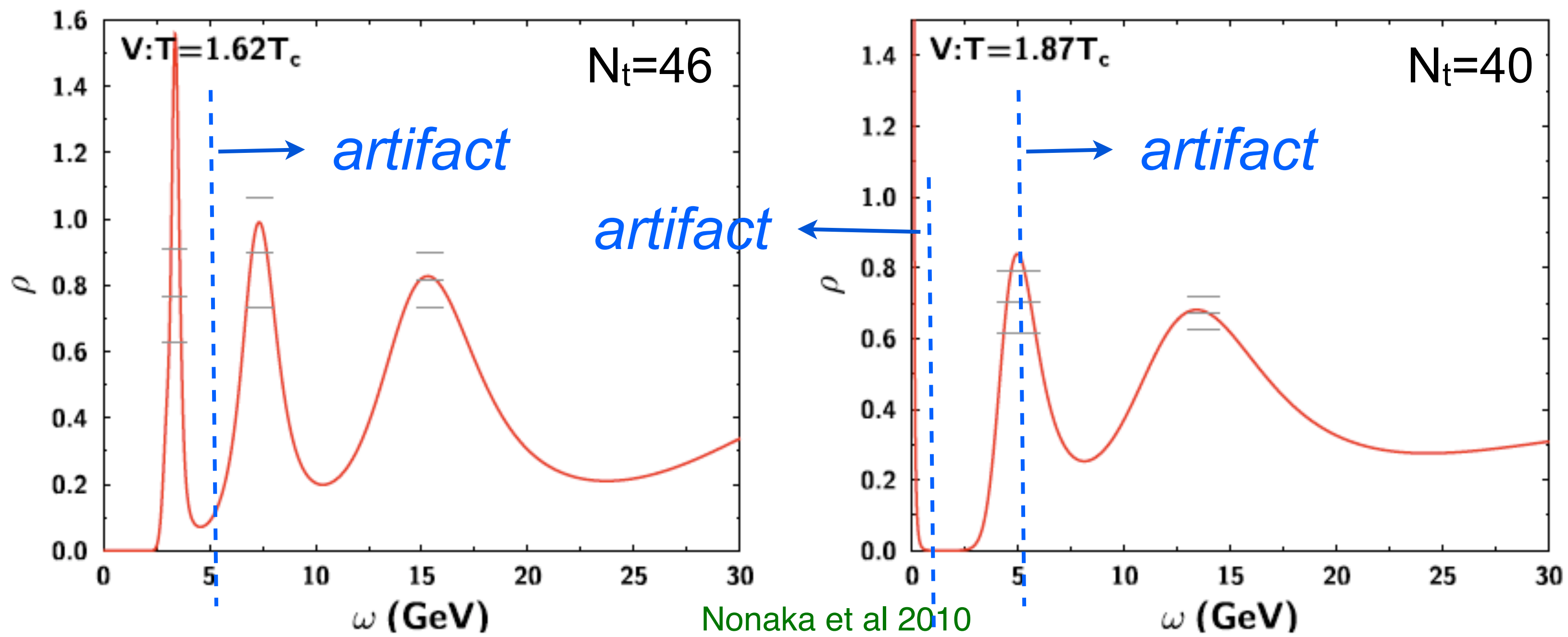

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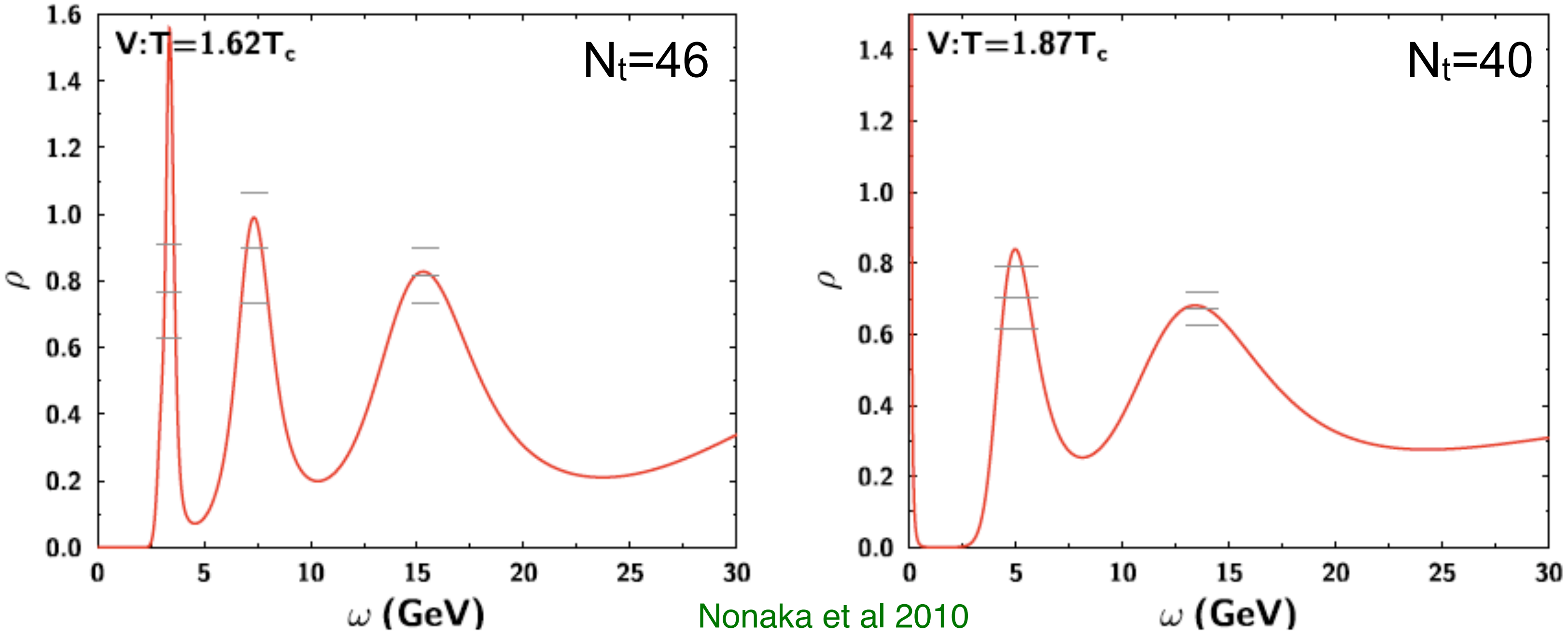

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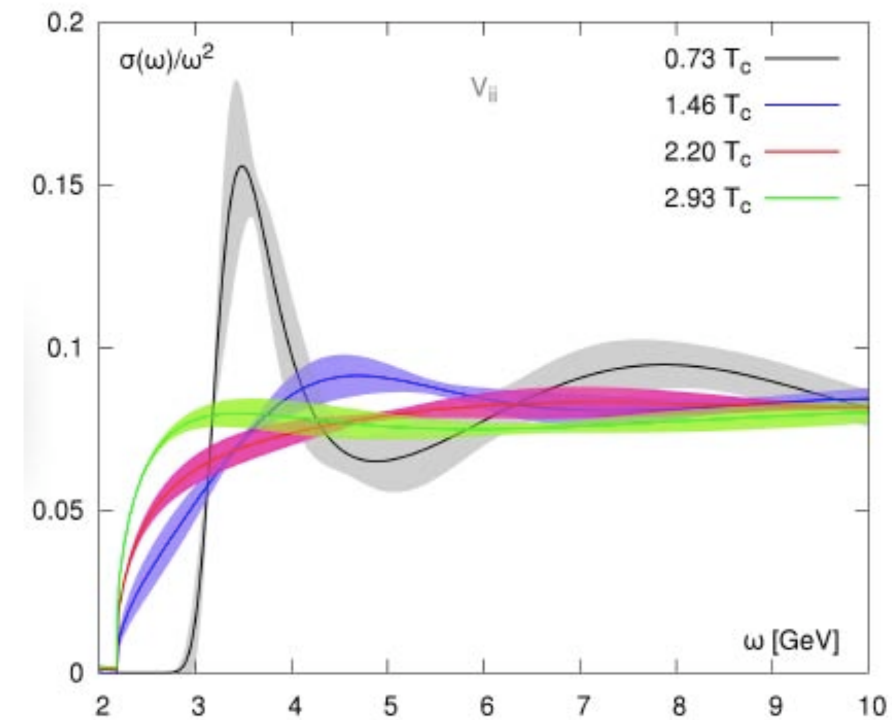


Ding et al 2010

prior: perturbative continuum spf (no lattice effects)

prior: from T=0 data at high energies

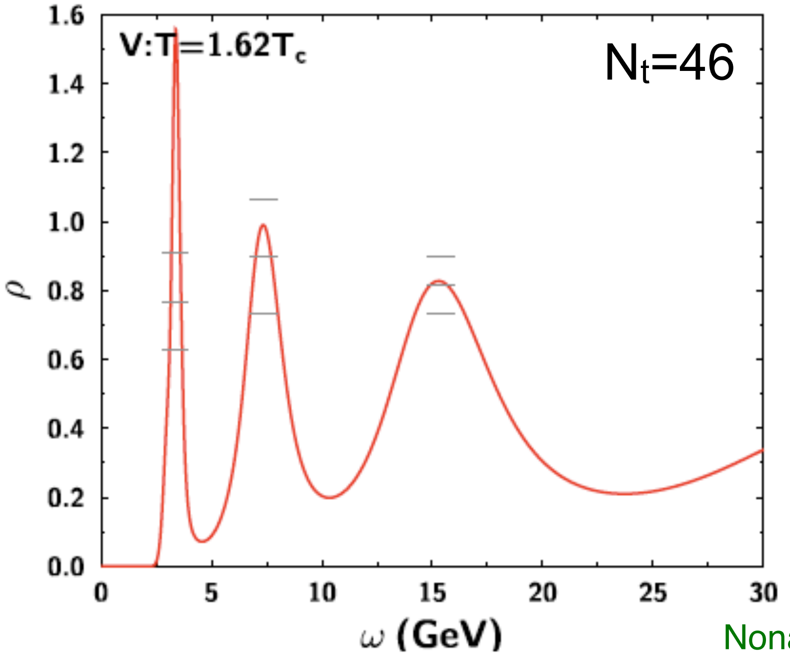
"We found that J/ψ is stable above the critical temperature T=1.62T$_c$"

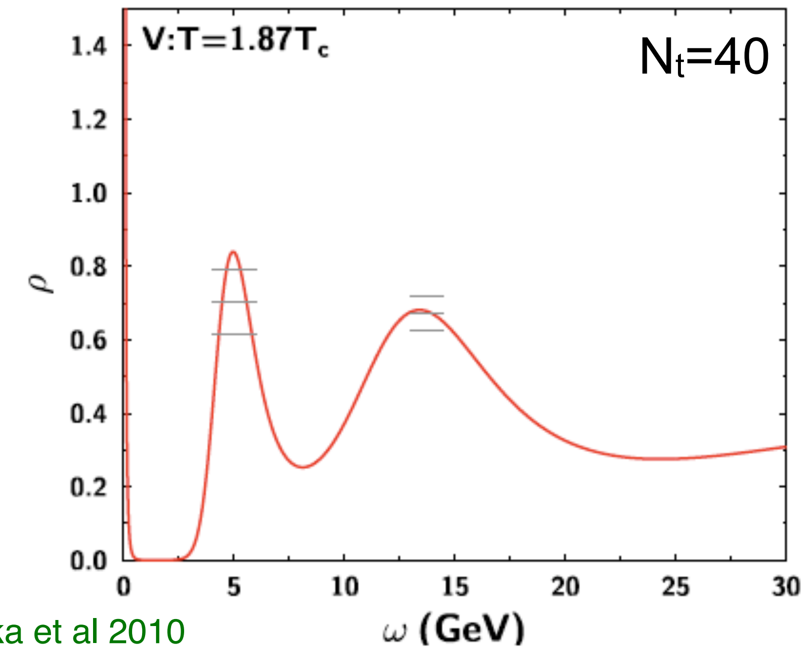
"Our analysis suggests that J/ψ is melted already by 1.46 T$_c$"

Charmonium Spectral Function

Extracted in quenched QCD

Most recent lattice results





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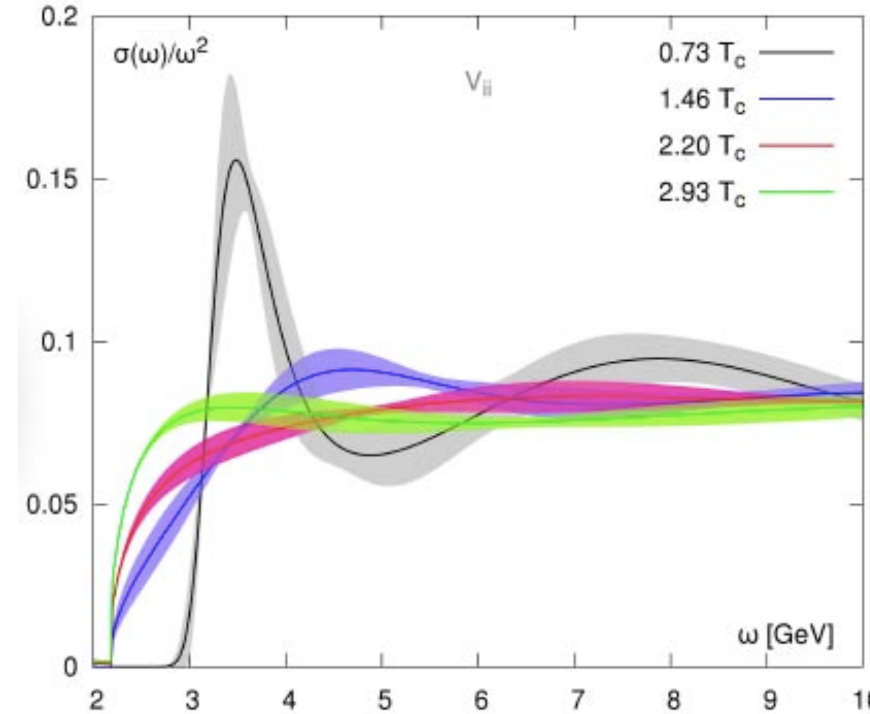

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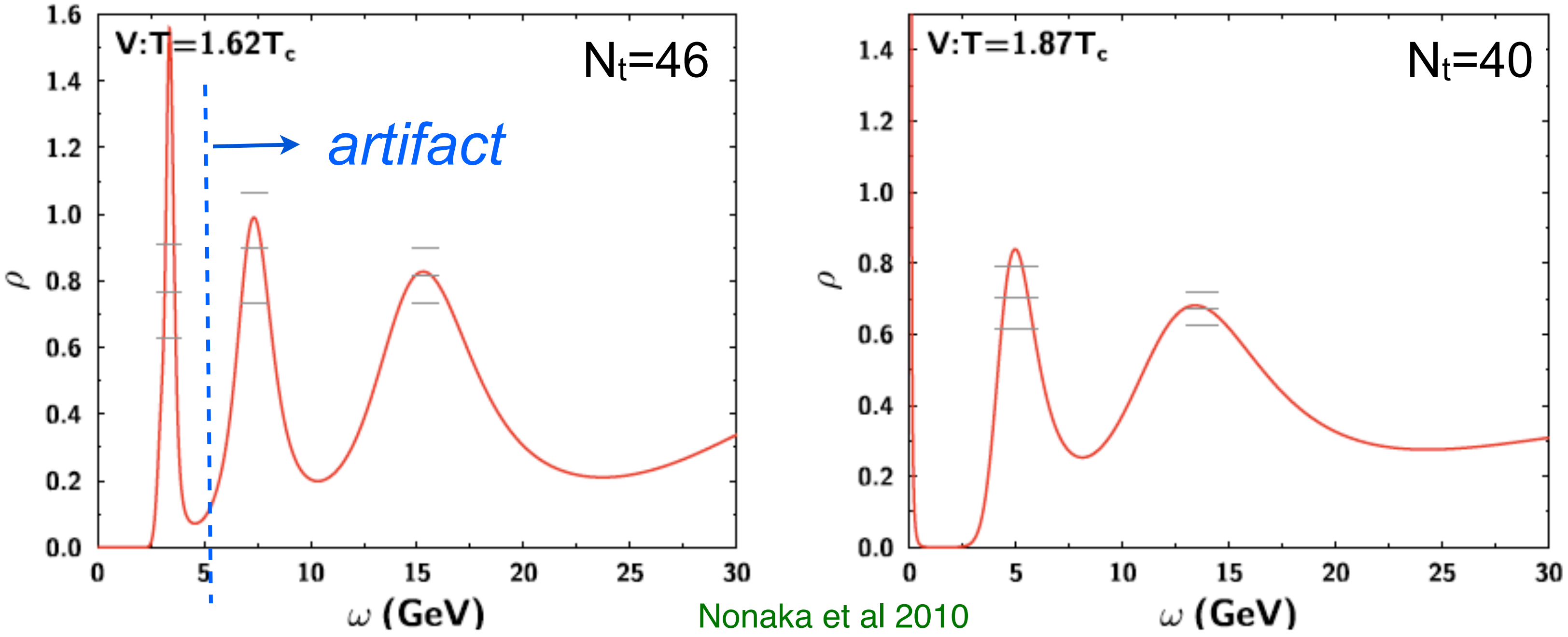

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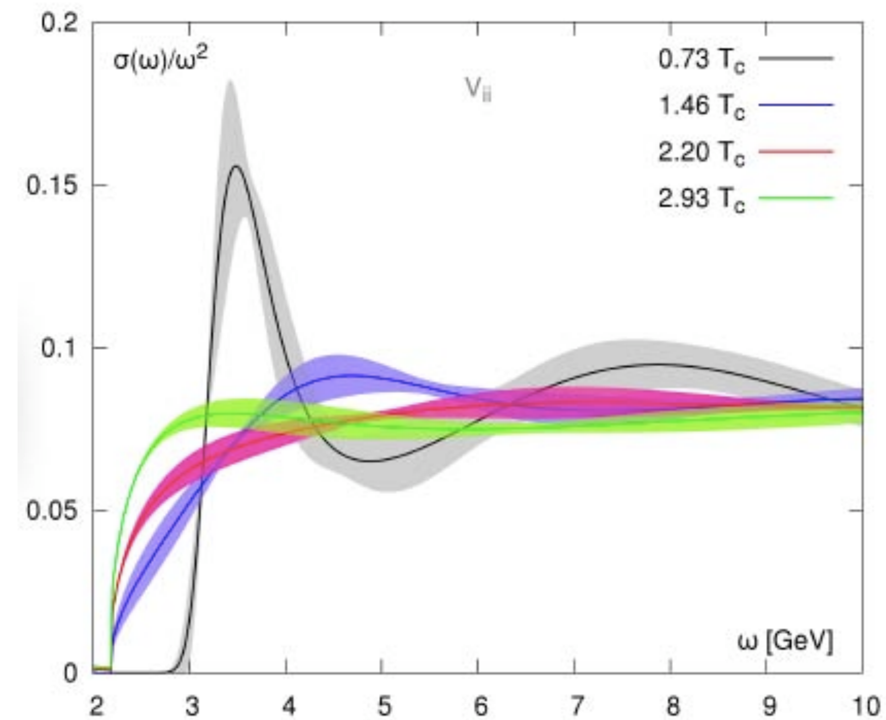

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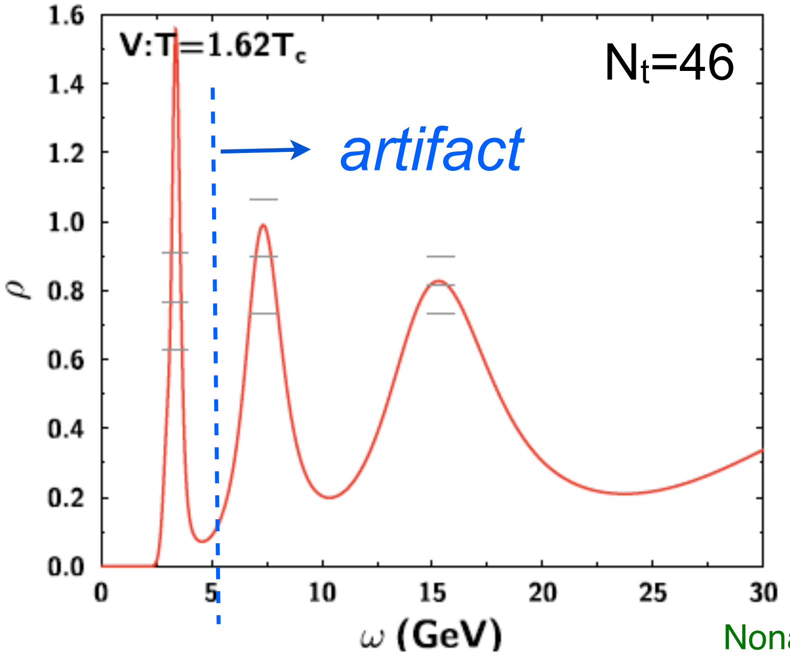

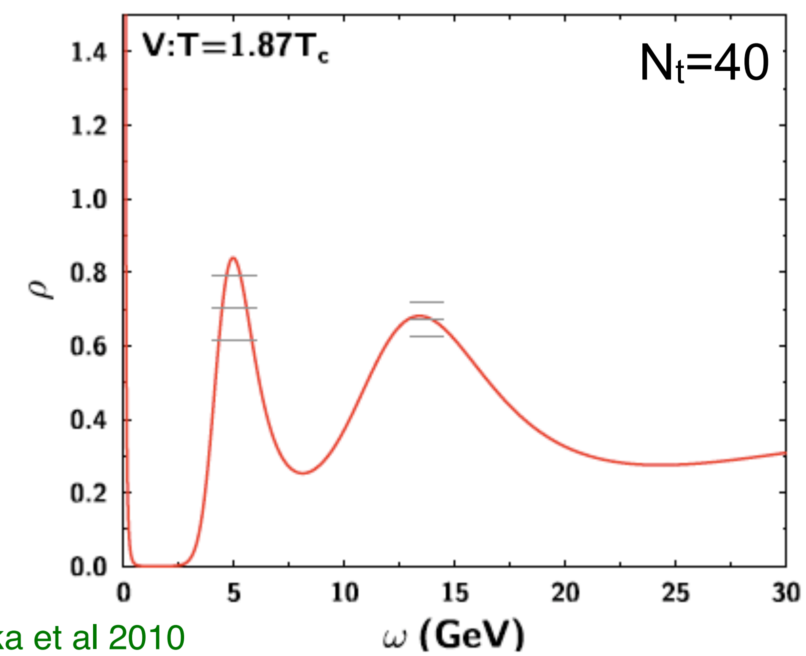

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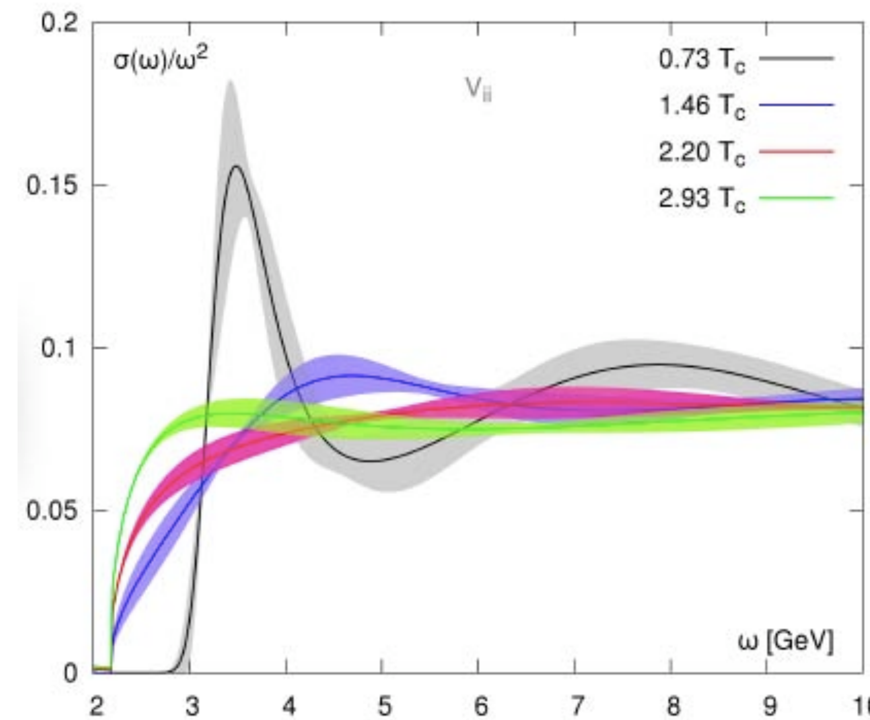

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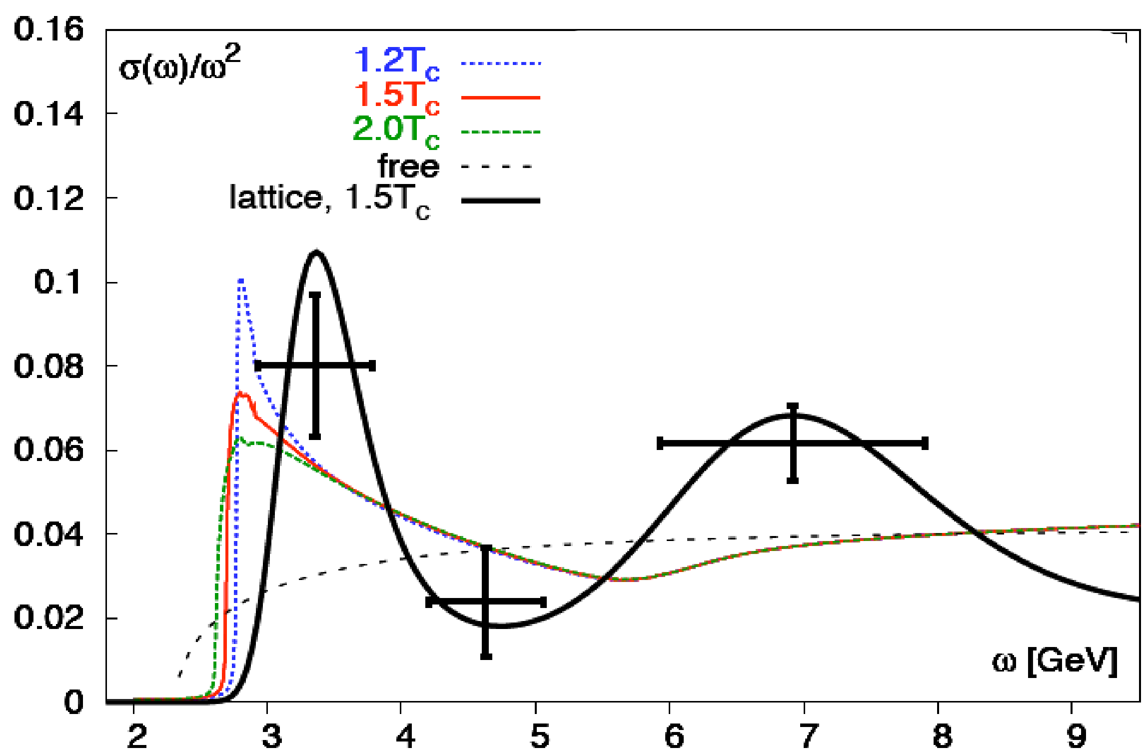
Even if we take all the 1st peaks seriously the claims are contradictory.

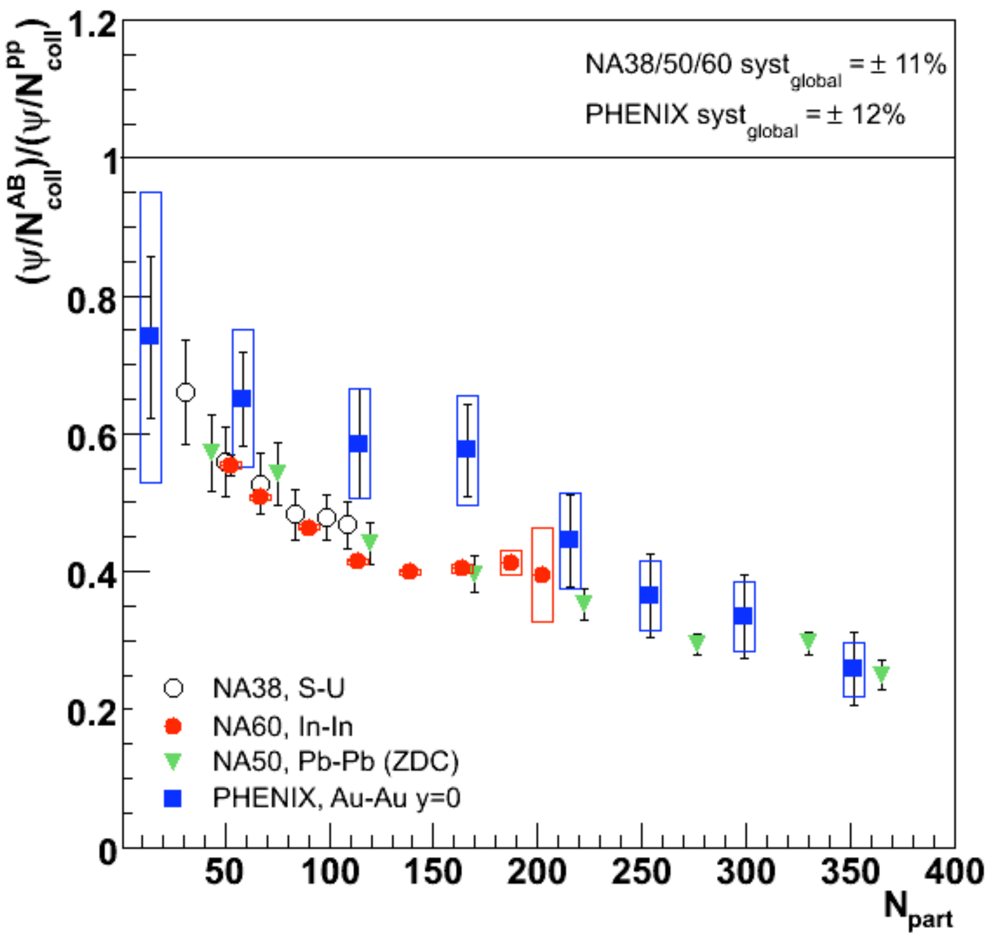
NB: widths have no physical meaning

It is difficult to make any conclusive statement regarding quarkonium at finite temperature based on the shape of the lattice spectral functions

Famous Plot

How can we relate these?



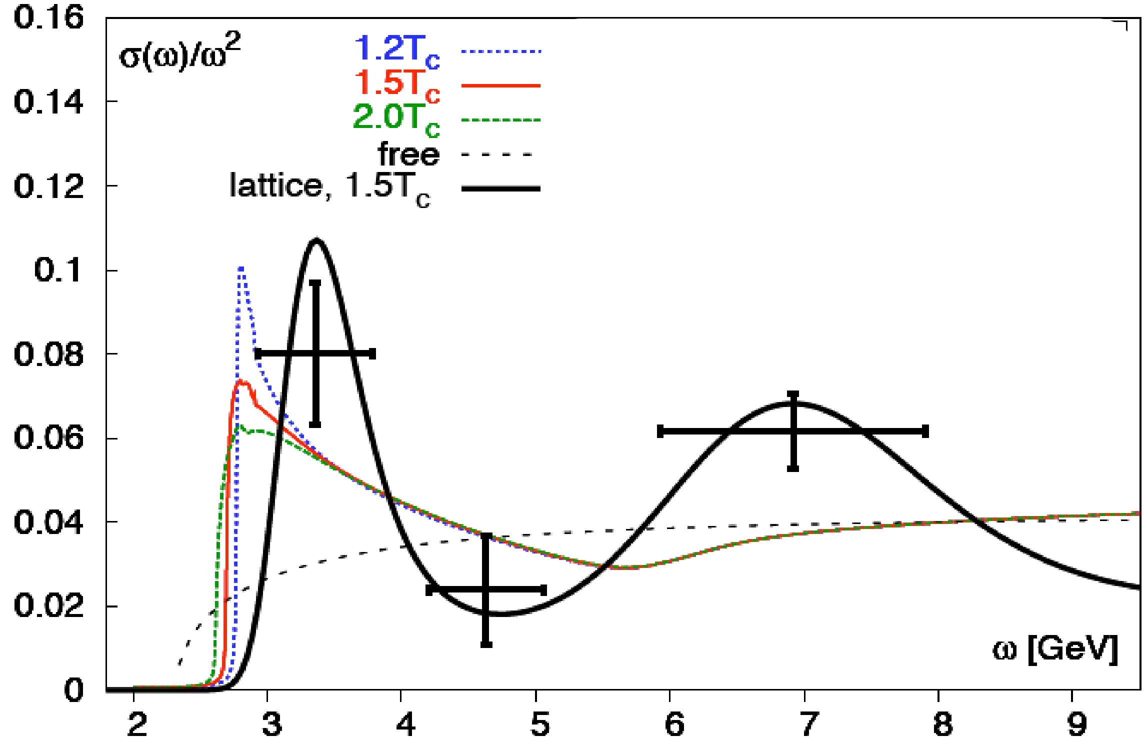


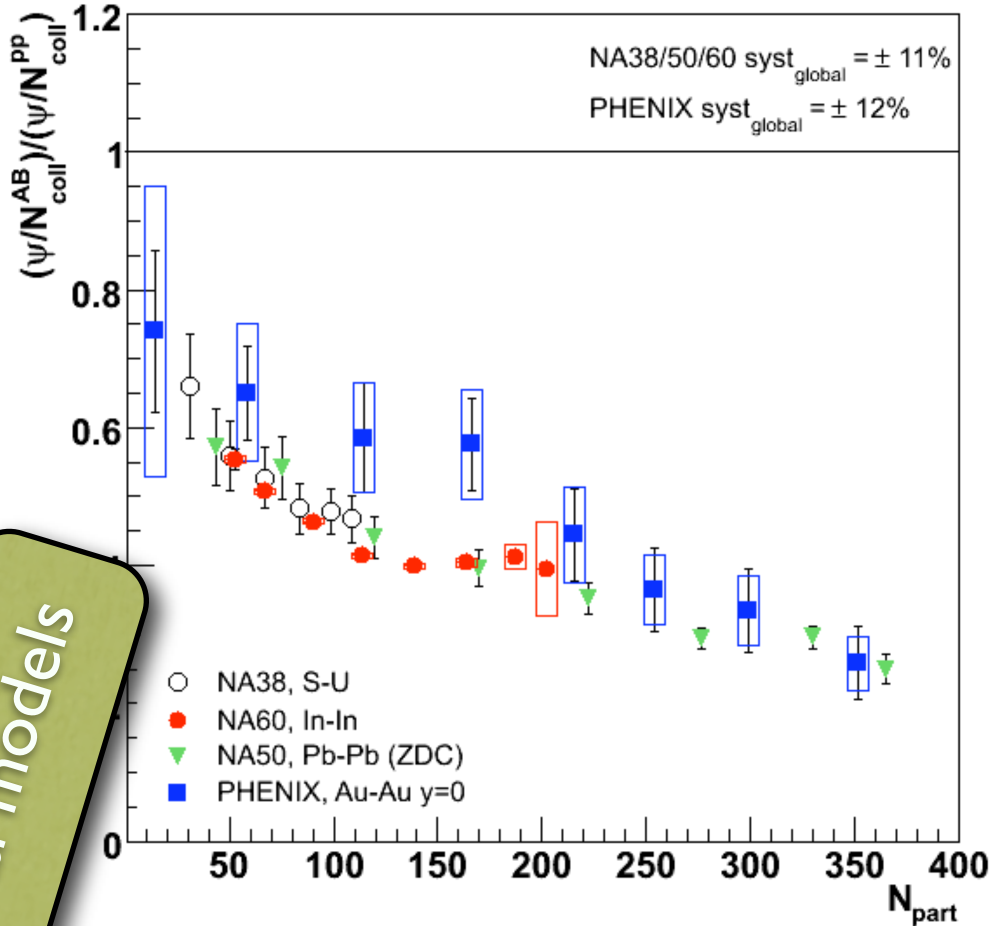
Quarkonium spectral functions in equilibrated plasma

Experimental data

Famous Plot

How can we relate these?





Quarkonium spectral functions in equilibrated plasma

Dynamical models

Experimental data

The Connection

Zhao, Rapp, van Hees, Fries, Young, Shuryak, ...

- Spectral function calculation → no bound states
  only correlated c-cbar pairs

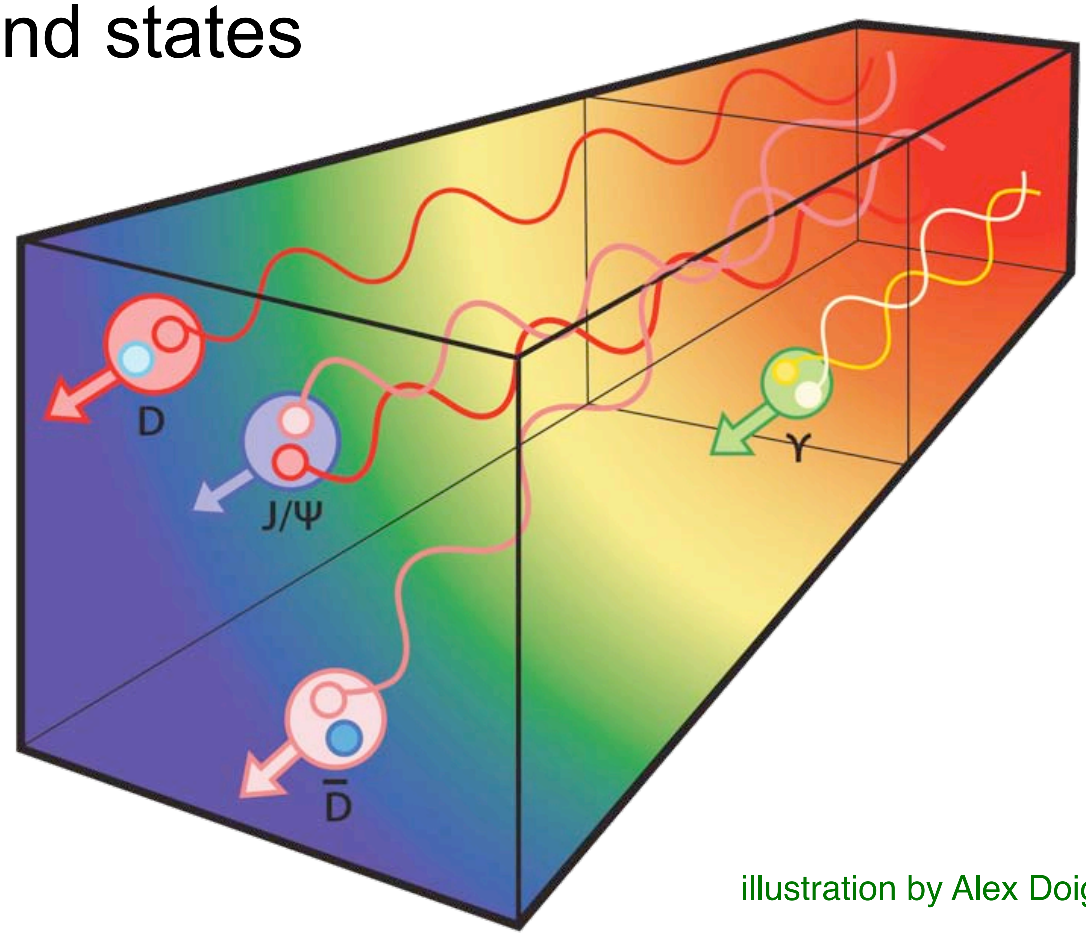


illustration by Alex Doig

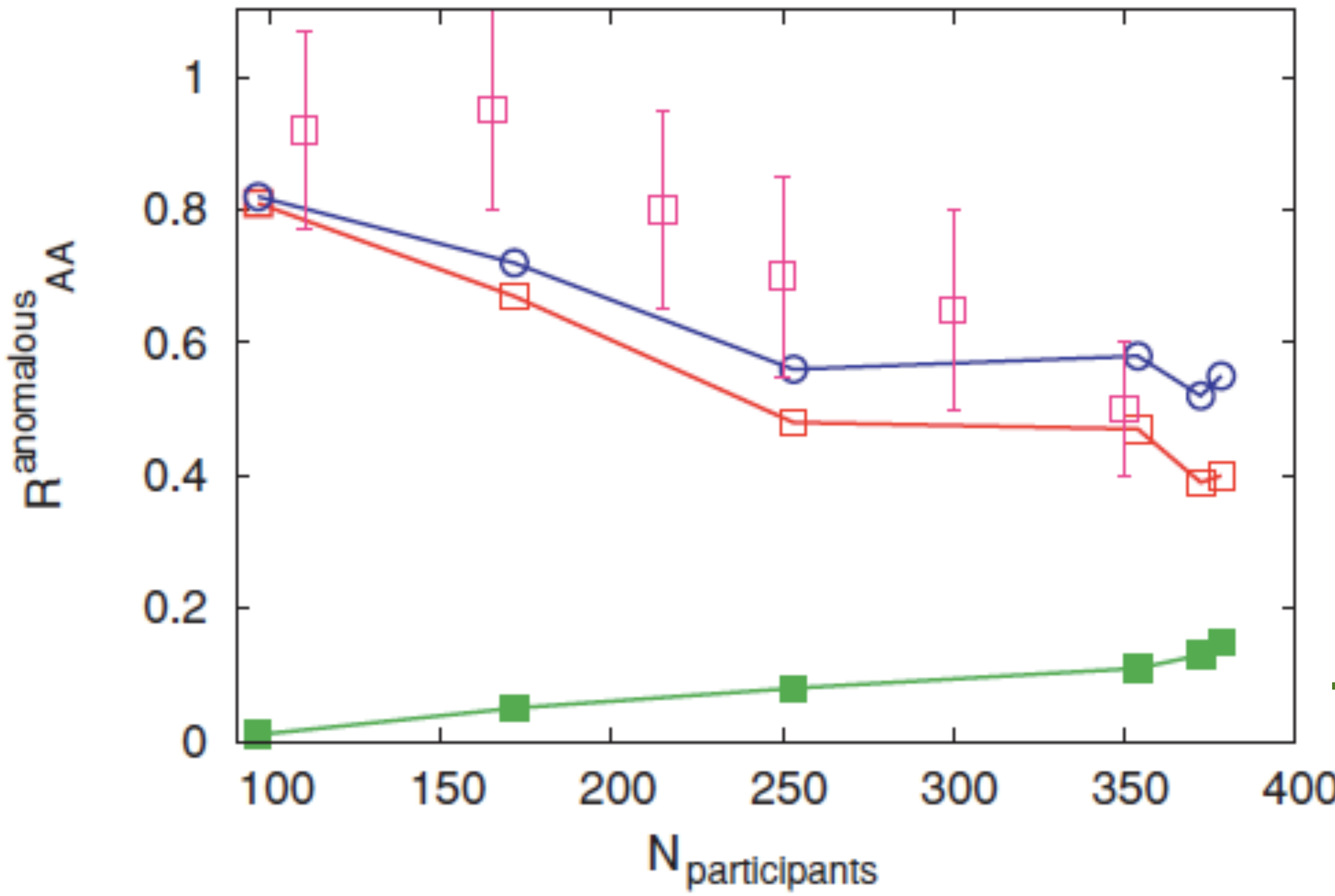
- What is the probability that c-cbar find themselves in proximity at the hadronization time?

- Modeling the motion of c-cbar in the evolving fireball
  according to Langevin dynamics
  - stochastic force from the heat bath
    - Input: charm diffusion constant
      Best current guess Teaney and Moore $D_c(2\pi T)$ = 1.5-3
      if small enough that attraction between c and cbar may survive
  - attractive interaction between c-cbar
    - Input: heavy quark potential
  - lifetime of the plasma

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010



- total yield
- suppression + correlated regeneration
- statistical recombination
  c and cbar originate from different hard processes

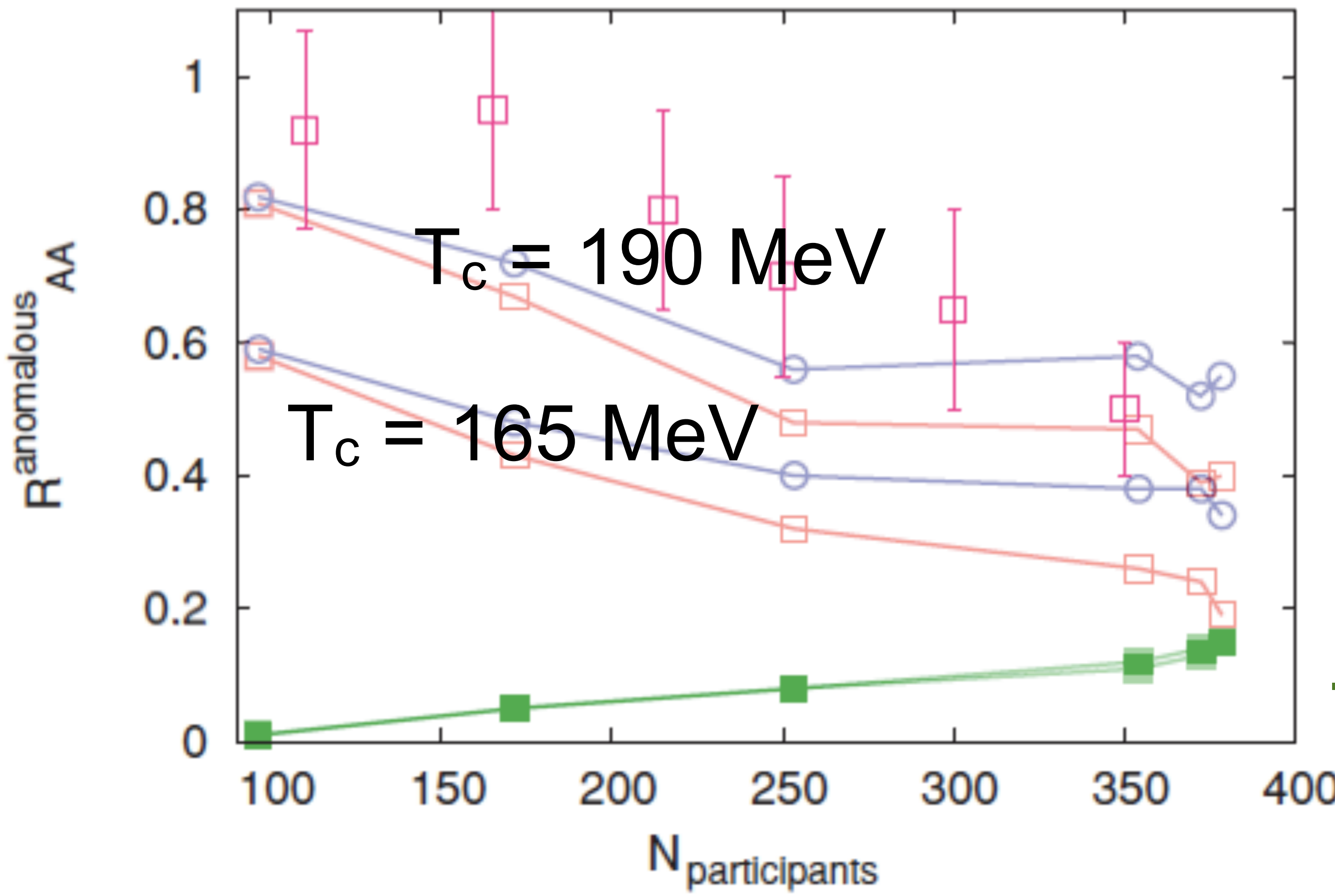
- Direct J/ψ suppressed, but ~ 50% of correlated c-cbar recombine
- Coalescence gives relative small contribution
- Quite good agreement with data for small charm diffusion and T_c=190 MeV

Note: $T_c = T_{deconfinement}$

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010



- total yield

- suppression + correlated regeneration

- statistical recombination
  c and cbar originate from different hard processes

- Agreement is better with the higher deconfinement temperature, i.e. with a shorter QGP lifetime

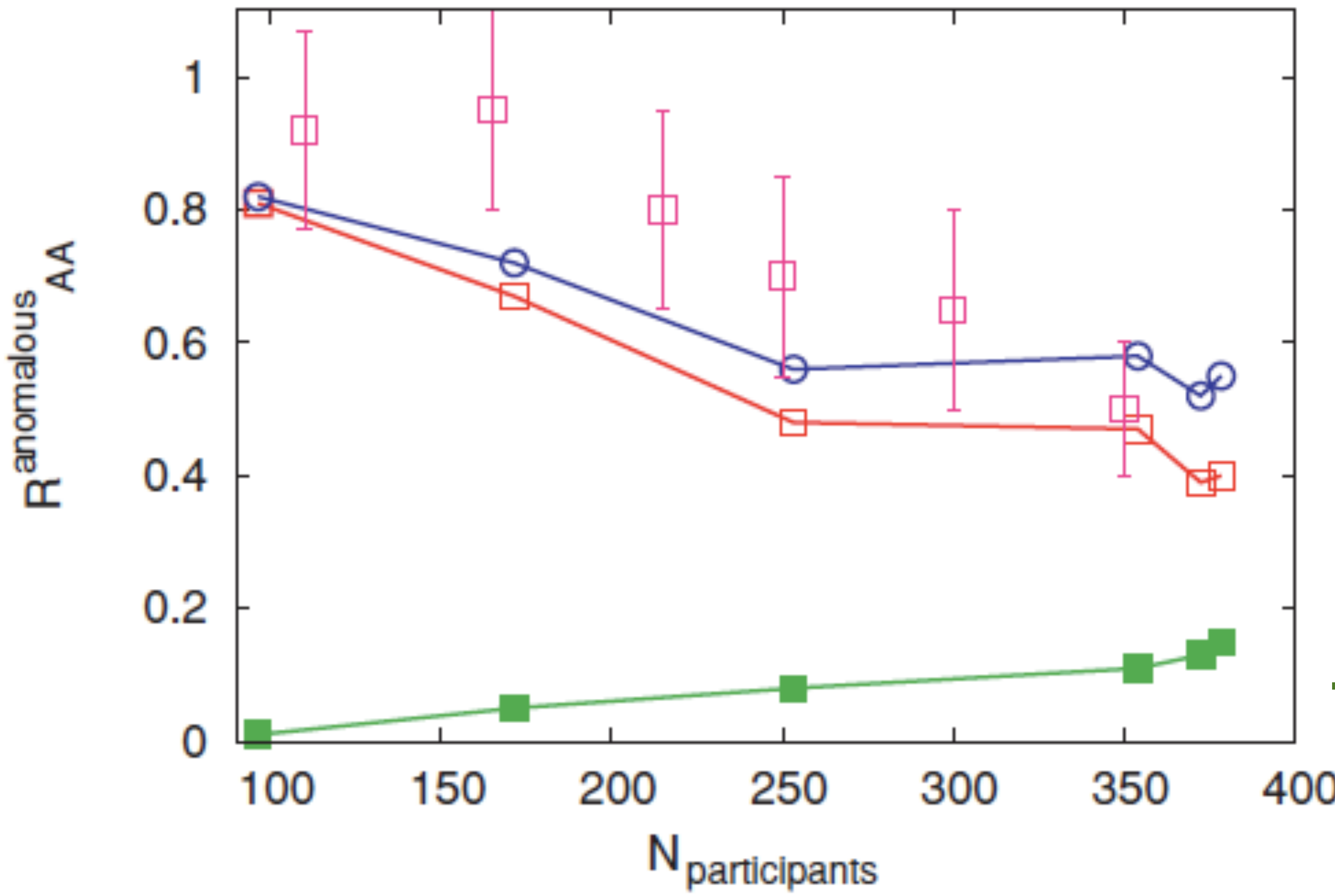
The finiteness of R_{AA} can lead us to determine the plasma lifetime ?!

Note: $T_c = T_{deconfinement}$

The Connection

- Comparison to PHENIX data

Young, Shuryak, PRC 2010



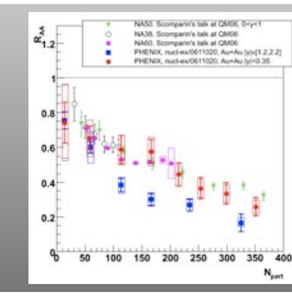
- total yield
- suppression + correlated regeneration
- statistical recombination
  c and cbar originate from different hard processes

- Note

  There are effects not included in this model: initial state effects and absorption in the crossover-hadronic region (CNM effects)

- A quantitative comparison with data is difficult

Can we isolate hot effects?



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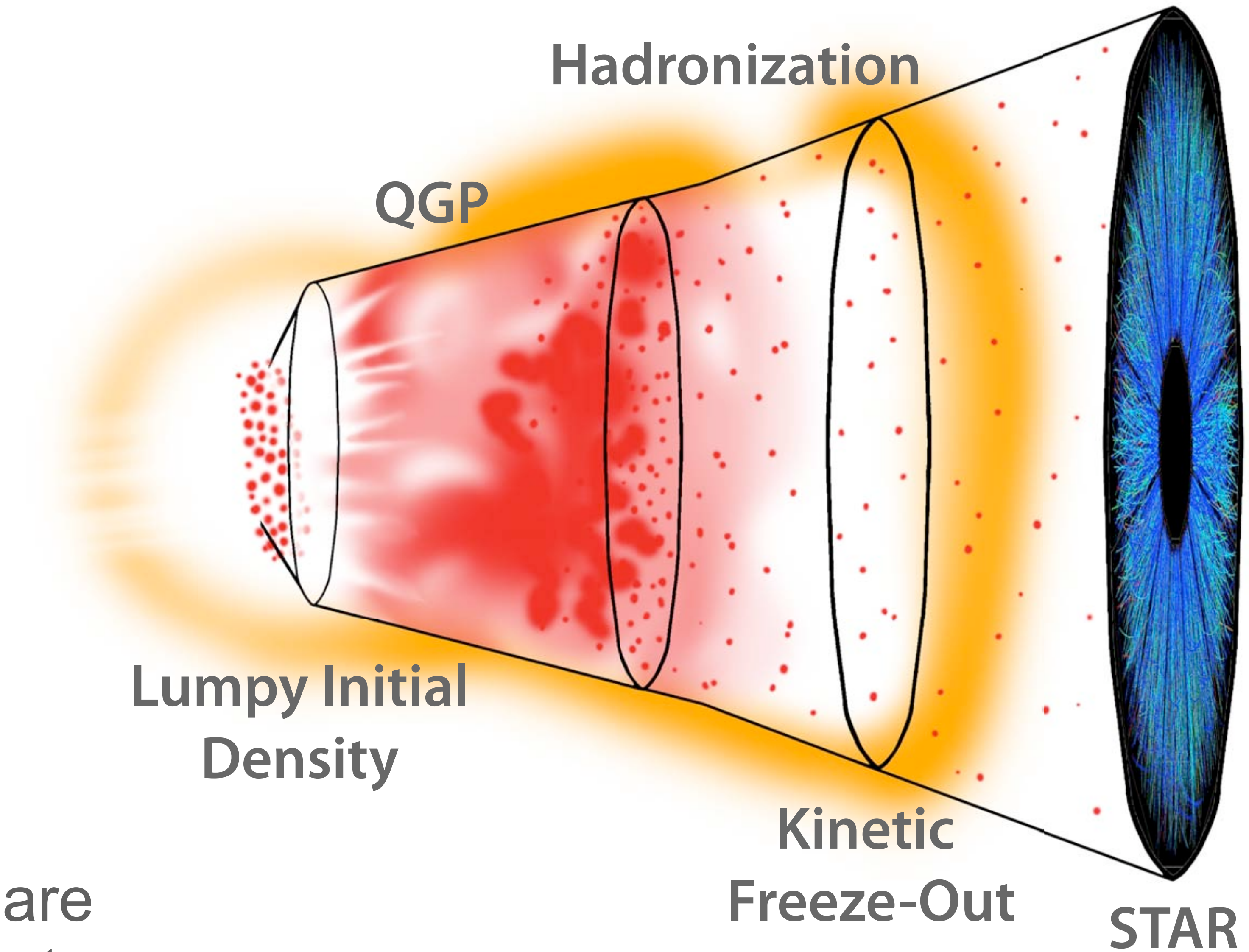

c and cbar are produced at early times ...

... go through the entire evolution ...

... end up in hidden (J/ψ) or in open (D) charm

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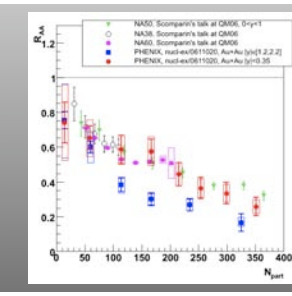

keywords

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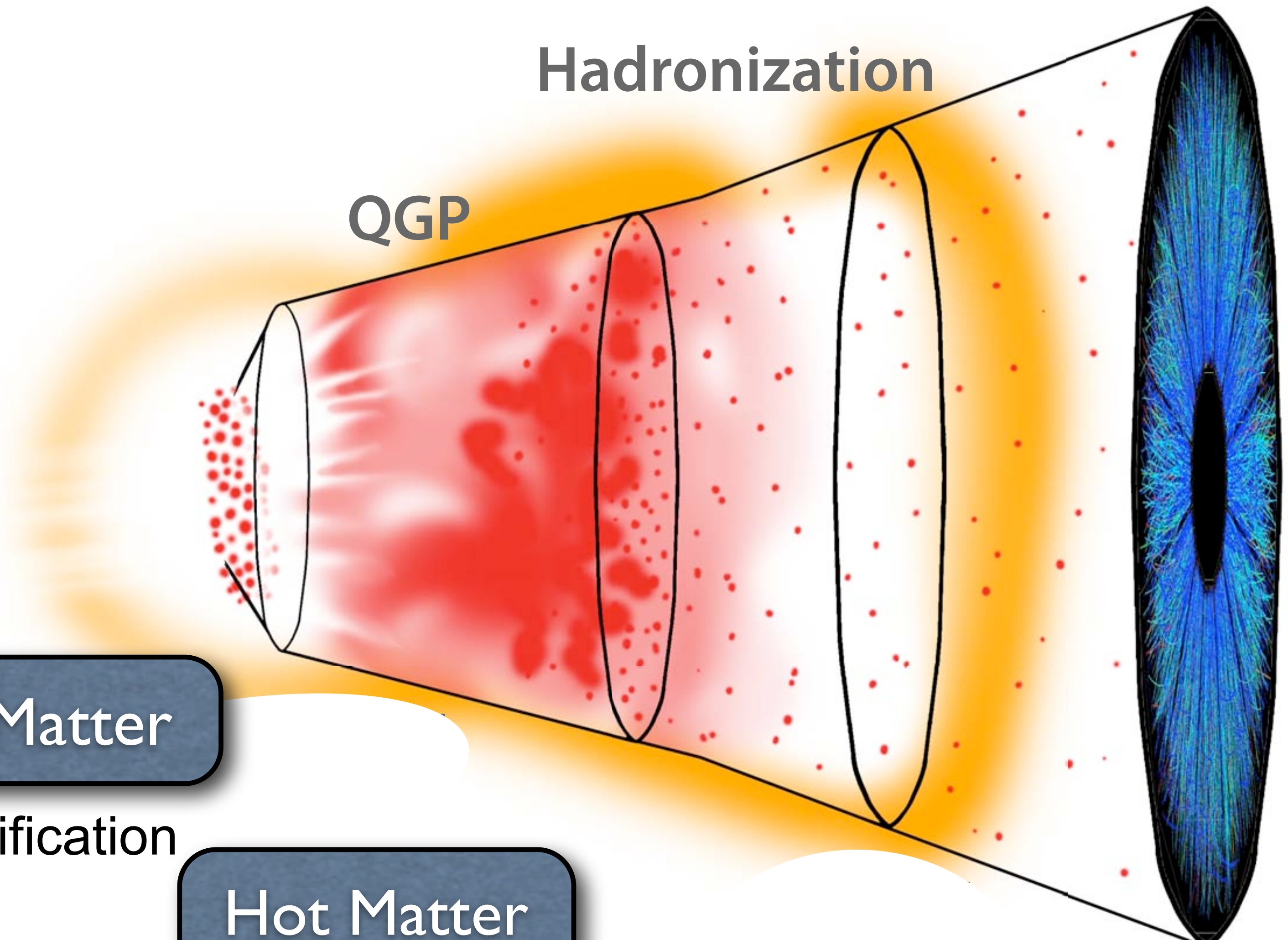


Cold Nuclear Matter

Initial: PDF's modification (shadowing)
Final: nuclear absorption

Hot Matter

screening
gluo-dissociation
Landau damping
threshold enhancement

Coalescence (regeneration)

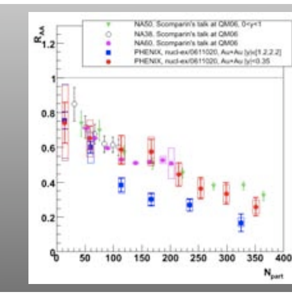
coalescence of single c quarks in the plasma

Hadronic Absorption

Feed-down

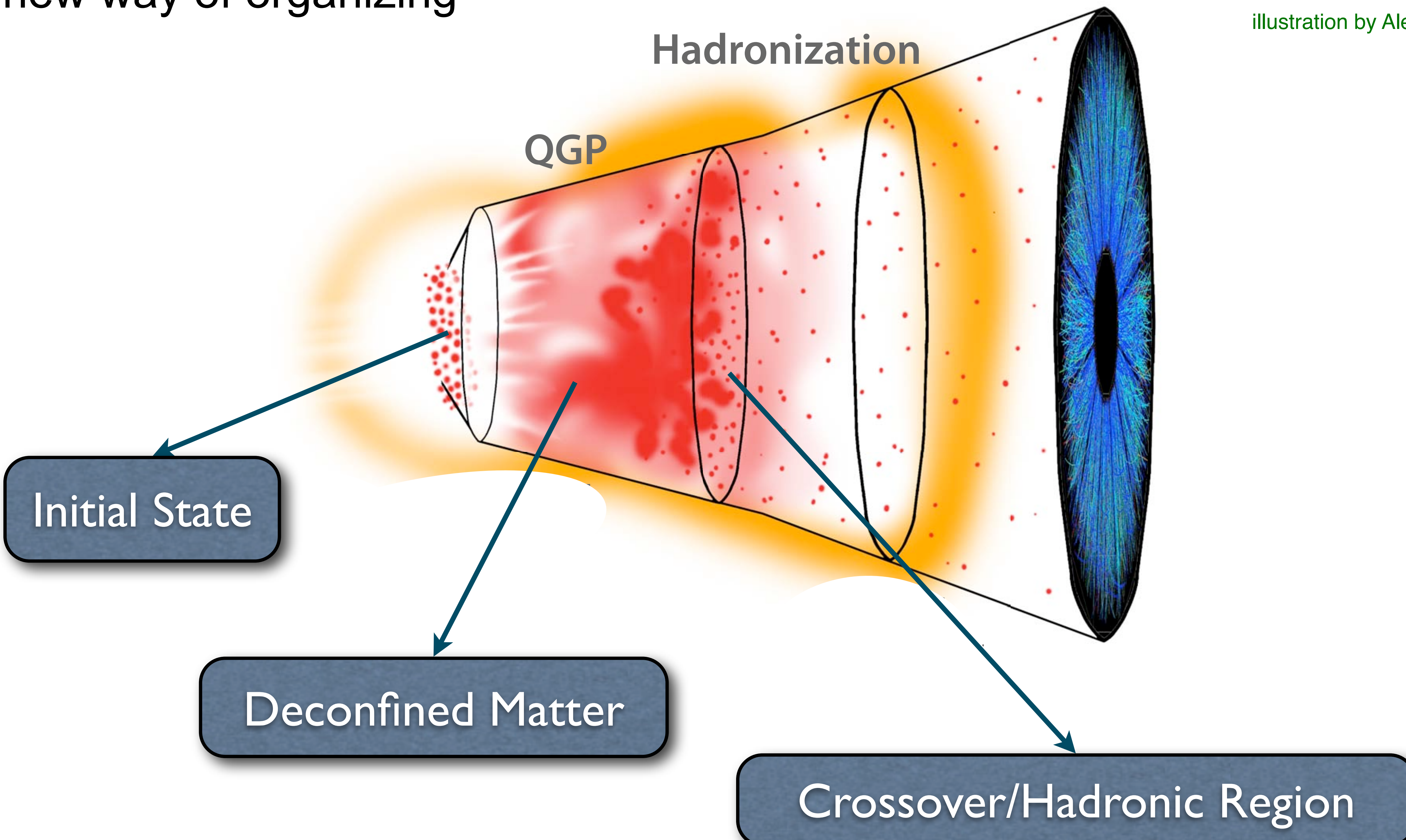
J/ψ from decays:
$\psi', \chi_c \rightarrow J/\psi$
$\chi_b, \Upsilon', \Upsilon'' \rightarrow \Upsilon$

Can we isolate hot effects?



new way of organizing

illustration by Alex Doig

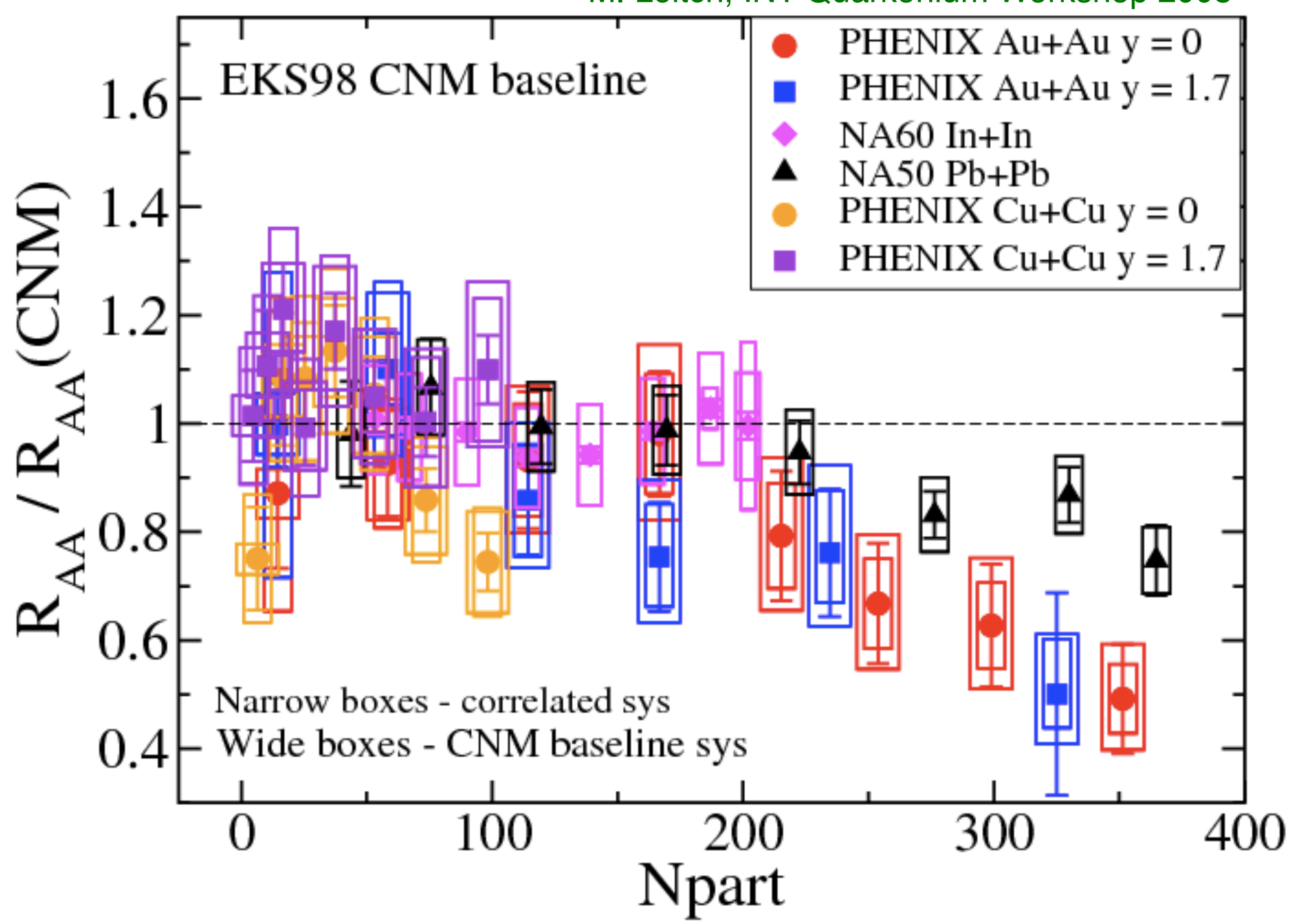


Can we isolate hot effects?

With CNM effects divided out

“Anomalous suppression”

M. Leitch, INT Quarkonium Workshop 2008



This makes sense if

- all CNM effects are initial state (shadowing), or
- absorption in the crossover region (“mixed phase”) is similar to absorption in nuclear matter

Can we isolate hot effects?

With CNM effects divided out

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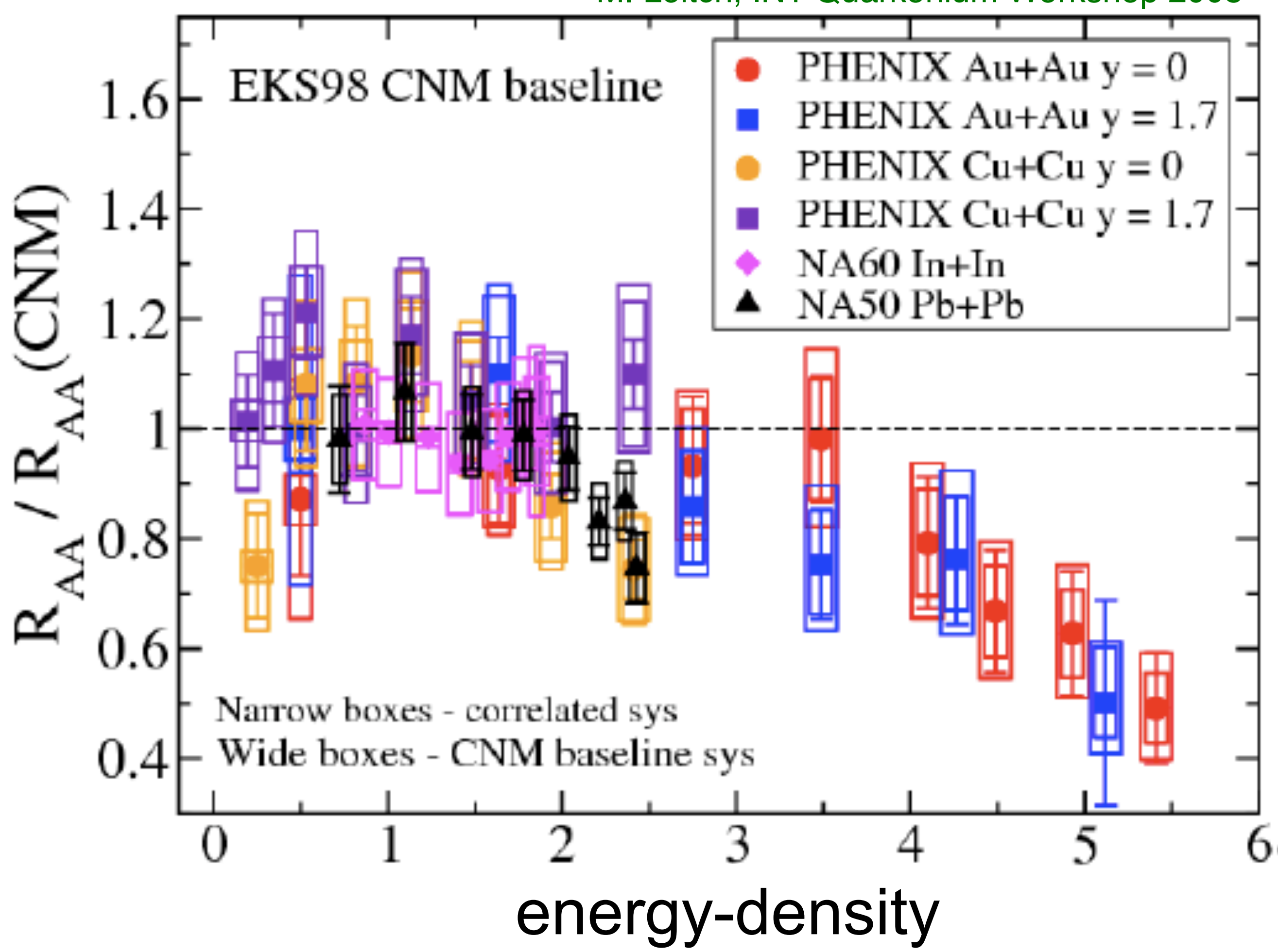


- SPS described well with hadronic - reaches into crossover region
- RHIC reaches into deconfined region

onset of deconfinement (onset of screening) ~ 3.5 GeV/fm^3 ~ 200 MeV

Other Controls

R_{AA} versus p_T

Great for separating the different contributions

At high p_T

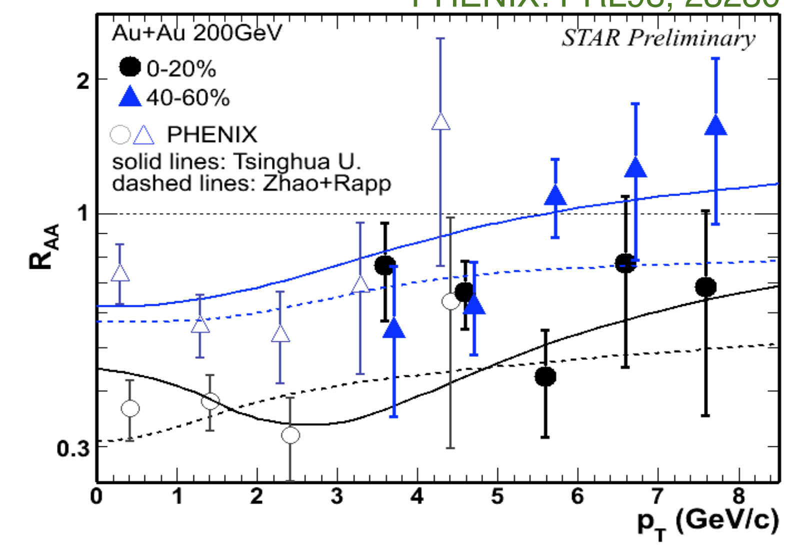
- CNM effects are less important: larger x
- Statistical recombination has little effect

- A suppression at high p_T would indicate suppression of direct J/ψ by the hot medium

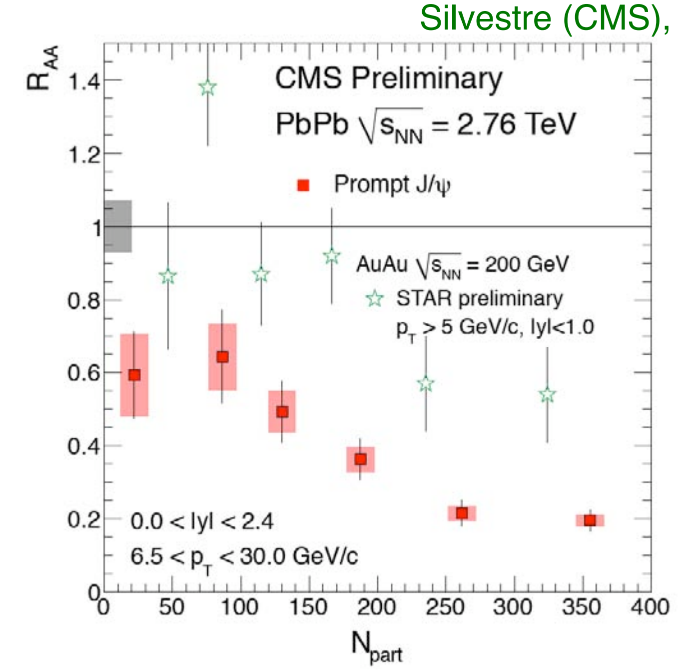
- If no suppression then J/ψ forms outside of (or after) the hot plasma. Formation time!

- larger high p_T suppression at LHC: can be from smaller x and/or longer lifetime

Zebo Tang (STAR), QM 2011
STAR CuCu: PRC80, 014922(R)
PHENIX: PRL98, 232301



Silvestre (CMS), QM 2011



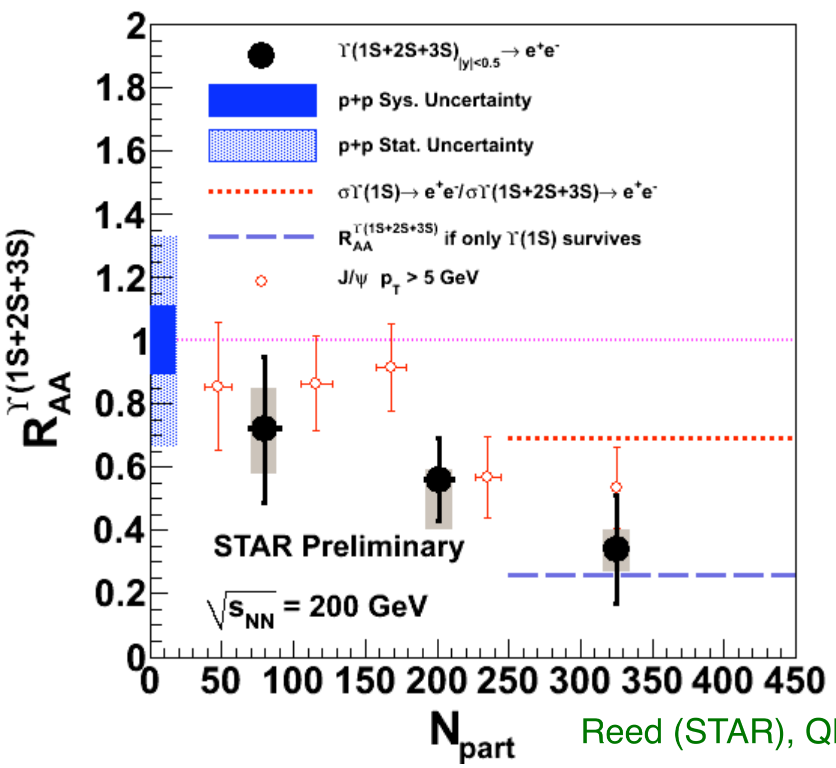
At RHIC: no suppression for J/y at high p_T (~5 GeV) in 200GeV Cu+Cu and peripheral Au+Au collisions, but suppression at high p_T in central Au
At LHC suppression persists to higher pT

Other Controls

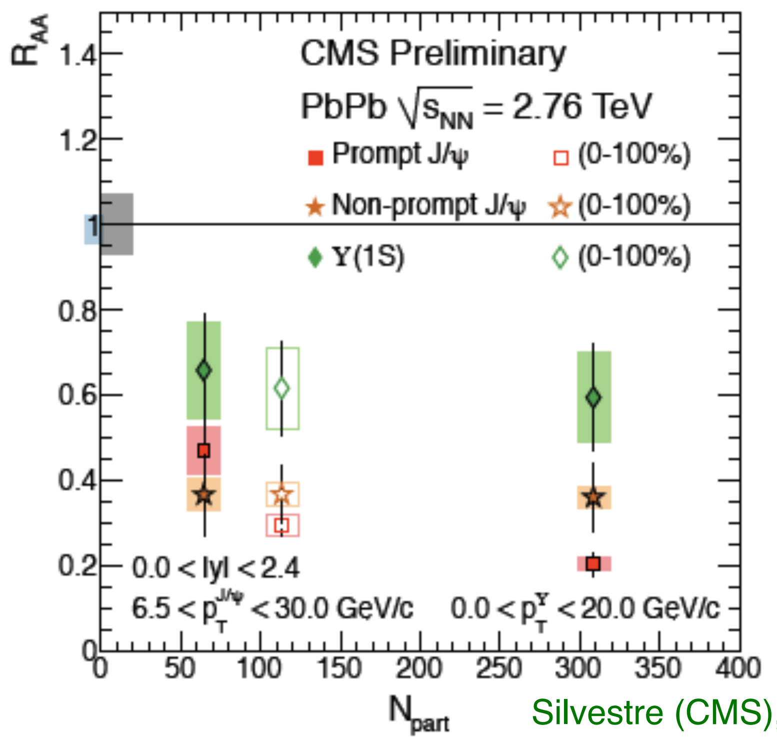
ϒpsilon

- ϒ (theoretically) is a much cleaner signal

- Initial state effects not very relevant ($m_b >> Q^2$)
- Absorption is small in the crossover/hadronic region
- No recombination: number of b and bbar is negligible (at RHIC)
- Easy to calculate spectral function, but dynamical modeling harder
- Ground state can survive at RHIC and be suppressed at LHC ?!



Reed (STAR), QM 2011



Silvestre (CMS), QM 2011

Summary

- EFT approach: Framework for systematic studies. The imaginary part of the potential plays a prominent role as a quarkonium dissolution mechanism.

- Spectral functions determined - with effects of color screening and dissipation
  - ✴ Even the most binding potential allowed by lattice QCD it leads to the dissolution of the 1S charmonium & excited bottomonium states by $T \approx 240$ MeV and of the 1S bottomonium states for $T \approx 450$ MeV
  - ✴ Consistent with most recent charmonium spectral functions from lattice
  - ✴ Different mechanism behind melting of charmonium and bottomonium
  - ✴ Threshold enhancement has phenomenological consequences

- Dynamical bridging necessary to make comparison to data - heavy quark diffusion, strength of Q-Qbar correlation, lifetime of deconfined medium

- High pT - as clear hot matter signal

The End